Motor unit firing patterns in light manual work
– with special reference to the etiology of chronic muscle pain in computer users

STEFAN THORN

Department of Product and Production development/Human Factors Engineering,
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2002
Motor unit firing patterns in light manual work
– with special reference to the etiology of chronic muscle pain in computer users

© Stefan Thorn, 2002

Report no 6
ISSN 1651-0984

Published and distributed by:
Department of Product and Production development/Human Factors Engineering
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone + 46 (0) 31 772 1000

Printed by Bibliotekets reproservice at Chalmers University of Technology
Göteborg, Sweden 2002
Motor unit firing patterns in light manual work
– with special reference to the etiology of chronic muscle pain in computer users

STEFAN THORN
Department of Product and Production development/Human Factors Engineering
Chalmers University of Technology
SE-412 96 Göteborg, Sweden

Abstract

Work related musculoskeletal disorders (WMSDs) in the shoulder/neck area and the upper extremities are a common problem among computer operators, especially women. A frequent type of WMSDs in the shoulder/neck area, which also may exist in the upper extremities, is chronic muscle pain (myalgia). The mechanisms for the development (etiology) of myalgia in the shoulder/neck area and in the upper extremities, in spite of the usually low muscle load levels in these muscles, are not fully understood.

This thesis has explored current knowledge of WMSDs among computer users and has investigated especially the validity of the so-called Cinderella hypothesis, which may explain the etiology of myalgia among computer users. The Cinderella hypothesis postulates that some groups of muscle fibres belonging to low threshold motor units (MUs) will remain active as long as the overall muscle activity exceeds a certain threshold level. In the context of monotonous workloads, e.g. computer work, this recruitment behaviour would cause an overuse of selective muscle fibres leading to muscle tissue damages, which in turn induce myalgia.

This thesis reports the results of three experimental studies of muscular activity in healthy human subjects. The subjects carried out short term and long term work tasks mimicking real life computer workloads. Intramuscular electromyography (EMG) measurements were made in a shoulder muscle (m. trapezius) and a finger/wrist muscle (m. extensor digitorum communis, EDC). By decomposition of the intramuscular EMG signals into short segments and classification of the segments into specific MU groups, MU firing patterns could be analysed for each test subject carrying out various work tasks such as in computer work.

The results show that there is a possibility for low threshold MUs to be continuously active in the trapezius muscle and the EDC muscle during long term work tasks such as in computer work. These results support the Cinderella hypothesis on a selective overuse of specific low threshold MUs in the context of computer work. Only some of the studied low threshold MUs showed this continuously active behaviour however, while others were active intermittently, which might be a result of MU substitution.

Finally, still open and important questions include how long a continuous activity or which firing pattern is needed for the muscle cells to become damaged and how the pain generation process leading to myalgia functions.

Keywords: monotonous work, myalgia, Cinderella hypothesis, intramuscular electromyography, motor units, decomposition, trapezius muscle, extensor digitorum communis muscle.
List of papers

This thesis is based on the following publications, which will be referred to in the text by their Roman numerals.


Acknowledgements

I would like to thank my supervisor, Associate Professor Mikael Forsman, for his outstanding engagement and personal concern in my research work and my general well being. I have truly enjoyed our co-work and look forward to its continuation. Furthermore, I give special thanks to Licenciate of Medicine Quixia Zhang and Associate Professor Susan Hallbeck for creative co-authorship and to Gunilla Zachau for invaluable support in the analyse. I would also like to thank Professor Roland Kadefors for his assistance and our fruitful discussions during the writing phases of this thesis. Thanks also to all my colleagues at the National Institute for Working Life; you are all wonderful to work together with!

Finally, I want to gratefully acknowledge VINNOVA (the former RALF) for funding this work.
**List of abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNS</td>
<td>Central nervous system</td>
</tr>
<tr>
<td>CTS</td>
<td>Carpal tunnel syndrome</td>
</tr>
<tr>
<td>CV</td>
<td>Coefficient of variation</td>
</tr>
<tr>
<td>ECR</td>
<td>Extensor carpi radialis muscle</td>
</tr>
<tr>
<td>ECU</td>
<td>Extensor carpi ulnaris muscle</td>
</tr>
<tr>
<td>EDC</td>
<td>Extensor digitorum communis muscle</td>
</tr>
<tr>
<td>EMG</td>
<td>Electromyography</td>
</tr>
<tr>
<td>EVA</td>
<td>Exposure variation analysis</td>
</tr>
<tr>
<td>FCR</td>
<td>Flexor carpi radialis muscle</td>
</tr>
<tr>
<td>FPS</td>
<td>Firings per second</td>
</tr>
<tr>
<td>MMG</td>
<td>Mechanomyography</td>
</tr>
<tr>
<td>MPF</td>
<td>Mean power frequency</td>
</tr>
<tr>
<td>MU</td>
<td>Motor unit</td>
</tr>
<tr>
<td>MUAP</td>
<td>Motor unit action potential</td>
</tr>
<tr>
<td>MVC</td>
<td>Maximal voluntary contraction</td>
</tr>
<tr>
<td>MVE</td>
<td>Maximal voluntary electrical activity</td>
</tr>
<tr>
<td>RMS</td>
<td>Root mean square</td>
</tr>
<tr>
<td>SEMG</td>
<td>Surface electromyography</td>
</tr>
<tr>
<td>VDU</td>
<td>Visual display unit</td>
</tr>
<tr>
<td>WMSD</td>
<td>Work related musculoskeletal disorder</td>
</tr>
</tbody>
</table>
1 Introduction

Work related musculoskeletal disorders (WMSDs) in the shoulder/neck area and the upper extremities are a common problem among computer operators, especially women (Wigaeus Tornqvist et al., 2000; Öberg and Åström, 2000). With respect to the shoulder/neck area, it is a general belief that many of the disorders can at least partly be referred to as muscular disorders, causing e.g. muscle pain (myalgia). There are also indications of the existence of muscular disorders in the upper extremities (Ranney et al., 1995; Ljung et al., 1999). Findings from a study of employees with highly repetitive work tasks, i.e. supermarket cashiers, indicate that the majority of the muscular disorders in these two regions are situated in the trapezius muscles and in the forearm extensor muscles, respectively (Ranney et al., 1995).

The problems have increased with increased computer usage (Wigaeus Tornqvist et al., 2000; Fogleman and Jeffrey Lewis, 2002; Blatter and Bongers, 2002). The use of computers in Sweden has increased dramatically, both at work (Wigaeus Tornqvist et al., 2000) and at home during the last few years. For instance, the number of hours for which modems are connected to the Internet has increased from 19 to approximately 120 billion between 1997 and 2001 for just one of the several net suppliers in Sweden (Telia, 2002).

Computer work tasks often contain a high degree of monotony; 47% of the male and 67% of the female Swedish office employees working more than halftime in front of a visual display unit (VDU) reported monotonous text editing and data entering as their main work tasks (Wigaeus Tornqvist et al., 2000). The muscle loads in the shoulder/neck area and in the upper extremities are normally also relatively low during computer work. As an example two field studies of computer-aided design (CAD) operators demonstrated a median trapezius muscle activity of approximately 4% of the maximal voluntary electrical (MVE) activity (Jensen et al., 1998; 1999). Exposure variation analyses (EVAs) in the latter study showed an activity level between 3 and 7 %MVE during nearly half of the work time and between 1 and 15 %MVE during more than 80% of the work time, which again indicates a high degree of monotony. In addition, the forearm extensor muscle (including extensor digitorum communis, EDC) activities have been measured to be relatively static, with a median muscle activity of 5-7 %MVE (Jensen et al., 1998; Birch et al., 2000c) and 17 %MVE (Aarås and Ro, 1997).

The physiological mechanisms for a development of myalgia in the shoulder/neck area and in the upper extremities caused by low level, long term monotonous workloads, such as in computer work, are not fully understood. A better understanding is essential in order to produce scientifically well-founded work organisational recommendations and to treat patients with muscle disorders effectively. This thesis has explored current knowledge of myalgia among computer users and has especially investigated the validity of one of the theories explaining the etiology of monotonous, work related myalgia, the Cinderella hypothesis (Hägg, 1991).

1.1 Basic muscle physiology

There are three main types of muscles in the human body: (1) skeletal muscles, (2) smooth muscles and (3) cardiac (heart) muscle tissues. The muscles described and investigated in this thesis belong to the group of skeletal muscles.
1.1.1 The skeletal muscle

A skeletal muscle, e.g. the upper arm biceps, contains thousands of muscle fibres ranging between 10 and 80 µm in diameter (Guyton, 1981). The fibre lengths vary between different muscles but are often equal to the muscle length (millimetres to decimetres). The stimulation of muscle fibres into contraction is controlled by electrical impulse trains from motor neurons connected to motor axons running from the ventral root of the spinal cord to the innervated muscle (Figure 1). Each motor axon divides itself into several branches, and each branch innervates one muscle fibre. The system of one motor neuron and the muscle fibres it innervates is called a motor unit (MU), which is the smallest part of a muscle that can be selectively contracted. The number of muscle fibres connected to a MU can be from just a few up to several hundred (Guyton, 1981). In general, small muscles with exact controls (such as the muscles controlling eyeball movements) are composed by very small MUs (few fibres) while larger muscles with lower fine-control requirements (e.g. the shoulder muscles) contain, on an average, larger MUs (many fibres). The total muscle force produced depends on the numbers of MUs activated, the sizes of the activated MUs, and the stimulation frequency of each MU (typically 5-15 Hz during steady activation).

![Figure 1](image_url)

Figure 1. Organisation of the skeletal muscle. The figure shows the innervation between the spinal cord ventral root (A) and the muscle (B). Darkened fibres together with the motor axon describe one MU. Adapted from McComas (1996).

1.1.2 The muscle fibre impulse train

When a muscle fibre is stimulated into contraction, an electrical impulse train is distributed from the innervation zone in both directions to the fibre endings. This impulse train is caused by a rapid change in the potential difference between the outer and inner cellular walls of the muscle fibre from approximately –60 to +35 mV. The change is called depolarisation and is followed by a recovery period called repolarisation (see Figure 1). The fibre cannot be triggered to contract within shorter intervals than approximately one millisecond, due to the so-called absolute refractory period.
1.2 Methods for measurement of muscular activity

Several different methods are now used within ergonomic science to physically measure the muscular activities that take place in the skeletal muscles during a work task. Two of them are electromyography (EMG) and mechanomyography (MMG). Among other methods available are, e.g., measuring intramuscular pressure changes, blood flow changes or tendon forces. These techniques are however not applicable for the detection of MU firing patterns and will not be further discussed here.

1.2.1 Electromyography

By using electrodes placed on the skin surface or inserted in the muscle it is possible to record electrical signals during a contraction of the muscle (Guyton, 1981). This well-established technique is called electromyography (EMG) and is often used for recording muscle activity in ergonomic studies (Kumar, 1996) and detecting signs for changes in muscle behaviour, e.g. fatigue (Kumar, 1996) or different traumas (Guyton, 1981). The signals originate from the impulse trains, which run through every activated muscle fibre (see Chapter 1.1.2) and diffuse straight across the fibres via organic tissues. The EMG signals are usually detected bipolarly, i.e. as the difference in electrical potentials between two recording points onto or inside the muscle, using one pair of electrodes. Indwelling bipolar configurations, inside a needle or via wire electrodes, are mounted intramuscularly and can therefore be positioned very close to the electrical sources of specific MUs. This enables together with a short inter-electrode distance between the two electrodes, denoted as a pair, a high spatial resolution of the EMG signal, making it possible to record EMG pulses originating from single MUs, so-called MUAPs (see Chapter 1.3.1). Weaker signals diffused from surrounding active muscle fibres are also recorded and create a background noise; this is however normally low enough not to hamper the decomposition. The MUAPs have relatively constant waveforms, each working as a fingerprint for a specific MU. This makes intramuscular bipolar EMG a potent method for obtaining data suitable for detecting firing patterns for several simultaneously active MUs.

When an extremity is in motion, the muscle is likely to move relative to the skin surface. Since intramuscular wire electrodes are able to follow these movements, which is difficult to achieve with needle electrodes, the position of the wires and thereby the electrode signal pick-up properties can be retained during dynamic work tasks (Kadefors et al., 1999). Wire electrodes are therefore suitable for studies of MU firing patterns during dynamic work tasks (Kadefors et al., 1999).
A further way to achieve better data for the detection of MU firing patterns is to record more than one channel of bipolar EMG. This can be achieved by using several intramuscular wire electrodes, where the recording points differ slightly in position between each electrode pair. This is sufficient to produce inter-channel differences in the MUAP shape for the same MU. In principle, a greater number of EMG channels will produce more data about the MUAP properties for each detected MU, which in turn will significantly simplify classification work (Forsman et al., 1999).

By using even shorter inter-electrode distances and smaller electrode contact areas, the recording volume of the bipolar EMG signals can be tuned to be very small. Hence, it becomes possible to detect single fibre action potentials from the EMG signal. As a consequence however, this approach offers a limited possibility to detect firing patterns for more than one MU at a time. Detection of single fibre action potentials has e.g. been used in order to obtain single fibre properties, such as propagation velocity, under various conditions (Stålberg, 1966).

If the inter-electrode distances and contact area of the electrodes are instead expanded, the complexity of the bipolar EMG signal will increase. Eventually it will be too complex to decompose successfully, as the activity of too many MUs will be detected at the same time (see Chapter 1.3). An expansion of distances and contact areas also results in the electrodes detecting the overall activity in large parts of the muscles or even whole muscles. Electrodes mounted onto the skin, so-called surface EMG electrodes, are generally used for that purpose. An indwelling method, where the EMG signal is obtained by using a monopolar (i.e. only one) intramuscular electrode with a large contact area, is however also common.

1.2.2 Mechanomyography
When a muscle contracts, the skin surface close to the muscle comes into motion. It is believed that this is excited by slow bulk movements of the muscle, vibrations at the muscle’s eigenfrequency (Barry, 1987; Frangioni et al., 1987) and pressure waves caused by muscle fibre dimensional changes (Orizio, 1993). The muscle contraction can thereby be detected via this mechanical motion by mounting sensitive accelerometers or microphones on the skin surface. This measurement technique is called mechanomyography (MMG). The MMG is currently not as widely used as EMG in ergonomic sciences. However, recent studies have shown that MMG may have a potential as a complement to EMG for e.g. detection of the mechanical activity of the muscle and muscle fatigue (Madeleine et al., 2001; 2002). Nevertheless, in the terms of detecting MU firing patterns, EMG so far shows an advantage over MMG owing to the relative simplicity of mounting electrodes intramuscularly and thus achieving a high spatial resolution of the signals.

1.3 Methods for detection of MU firing patterns
This chapter describes the basic methods for detecting MU firing patterns from EMG data, i.e. signal decomposition (see example in Figure 3). Common for all methods is that they are based upon segmentation of the EMG data into short signal segments, which is followed by classification of these segments into MU groups. This classification is made by comparing the waveform of each segment with the waveforms of the available motor unit action potential (MUAP) signals, which are used as fingerprints for each recorded MU.
Figure 3. Firing patterns for six different MUs, detected by the decomposition of 10 seconds of intramuscular EMG data recorded from the right trapezius muscle during a computer work task (adapted from Forsman et al., 2000).

### 1.3.1 The motor unit action potential

As mentioned in Chapter 1.2.1, the EMG technique records electrical signals originating from the impulse trains running through every activated muscle fibre during contraction of the muscle. The muscle fibres belonging to a specific MU are not triggered at exactly the same time when a MU is activated, since neither the location of the neuromuscular junction nor the conduction velocity is exactly the same for every fibre (Stashuk, 2001). These inter-fibre differences are relatively stable. For every MU firing occasion, each impulse train will thus in principal have the same time delay with respect to the other trains that are detected and that belong to the same MU. This will produce a particular EMG shape for each detected MU called the motor unit action potential, MUAP (see examples in Figure 4). In order to maintain this shape throughout the work task, however, it is important that the electrodes do not move in relation to the muscle fibres.

Figure 4. MUAPs from six different MUs, detected from the right trapezius muscle during a 20-second computer work task (adapted from Forsman et al., 2000).

The EMG data recorded at a certain point outside or inside the muscle are created by superpositions of all muscle fibre impulse trains within the recording volume. EMG data from a smaller recording volume will thereby be composed of superpositions of
the impulse trains from fewer muscle fibres. This will increase the probability of finding segments in the EMG signal that contain superpositioned electrical data only from muscle fibres belonging to one specific MU. These so-called non-overlapped segments, i.e. containing data from only one MU, are thus MUAPs for each respective MU detected at that particular recording point.

1.3.2 Segmentation of EMG data
The first step in the decomposition is to extract the active parts of the composite EMG signal and to divide them into short segments, each preferably containing only one MUAP (plus the signal noise at low amplitude from e.g. other MU signal sources far away from the electrodes). Some segments may, especially at higher muscle load levels, contain superpositions of two or more MUAPs, but this can often be handled later on by the classification algorithms. The segmentation can be done in various ways, but common for all methods is to find a detection threshold based on statistics computed from the composite signal (Stashuk, 2001). When the signal characteristics produce a statistic value above the threshold, some methods select a fixed length section that becomes a candidate segment for classification, while other methods use variable length segments based on an abortion threshold, again based on statistics calculated from the composite signal.

1.3.3 Classification of signal segments into specific MUs
“Classification” means sorting the segments into a number of groups or clusters, each containing MUAPs from a specific MU. Every group-member shall be more similar to another group-member than to a member of another group. The numbers of groups are not known in advance. Most algorithms are based on the single-linkage technique, which means that every segment is compared with the closest individual object (Stashuk, 2001), but comparison with cluster mean values, templates, by a complete-linkage technique is also possible. Since the MUAP shape varies slightly between firings, it may be difficult to achieve correct results with a single-linkage method. The MUAP shapes also often change in a common direction during long term contractions. Templates calculated by a complete-linkage technique may thus be influenced too greatly by their historical shapes, which could impair the classification.

Comparisons between a segment and a template can be achieved in many different ways. Parameters such as maximum slopes and amplitudes, areas enclosed by the waveforms, root mean square (RMS) of the residual value between segment and template, and wavelet and power spectrum parameters describing the waveforms can be used for this purpose. Apart from these comparisons, a minimum time inter-distance is often set for allowing clustering between two firings. This is based on the fact that the motor axon innervating a MU, and its muscle fibres, should not physically be able to fire faster than to a certain limit (see Chapter 1.1.2).

1.4 The development of myalgia
As mentioned, the mechanisms behind the development of myalgia caused by monotonous, low level workloads, such as in computer work, are not fully understood. There are however a few hypotheses. One theory postulates that the increased intramuscular pressure occurring during a muscle contraction will hamper the macrocirculation of blood through the muscle, thereby causing, e.g., ischemic pain and tissue necrosis. Another theory, the Cinderella hypothesis, suggests that the disorders occur instead on a muscle micro-level due to an overuse of specific muscle fibres.
1.4.1 Hampered blood macrocirculation
A hampered blood macrocirculation may in the long run cause an insufficient supply of oxygen and nutrition substances to the muscle and restrain the transport of residual products, such as lactic acids, from the muscle. These effects may then introduce muscular pain. In deeply situated muscles, and particularly when surrounded by rigid anatomical structures, this may be a possible risk. It is unlikely to occur in shallow muscles such as the trapezius muscle, however, since the intramuscular pressure loads taking place there during low level work tasks (Järvinen et al., 1991) generally are low enough to allow muscle fatigue recovery (Körner et al., 1984). Furthermore, studies of blood flow changes in patients with chronic neck-shoulder pain have shown that the pain can instead be associated with impaired microcirculation in the trapezius muscle (Larsson et al., 1998; 1999).

1.4.2 The vicious circle
Johansson and Sojka (1991) formulated a hypothesis describing the genesis and spread of muscular tension in patients with musculoskeletal pain syndromes. The model works as follows: A static muscle contraction (in primary muscles) causes a production of metabolites, which activates gamma-motoneurons projecting to both primary and secondary muscles. This activation increases the stretch sensitivity and discharges of primary and secondary muscle spindle afferents. These send signals from the muscle spindles, which are triggered by i.e. changes in muscle length, from the muscle to the central nervous system. The increased activity in these afferents intensifies the muscle stiffness, which in turn causes a further production of metabolites in primary and secondary muscles. The result is a vicious circle that spreads and increases the sensations of pain throughout a body region. However, in a review of articles on motor function under conditions of pain, Lund and Donga (1991) concluded that the agonist muscle activity is instead inhibited by pain, in both painful and healthy muscles, which contradicts the hypothesis of Johansson and Sojka. Furthermore, studies of the upper trapezius activity in workers with and without shoulder/neck disorders indicated that subjects with pain carry out the tasks at lower maximum load levels as compared with controls, while the degree of muscle rest was significantly lower in the controls (Hägg and Åström, 1997; Sandsjö et al., 2000).

1.4.3 The Cinderella hypothesis
Henneman et al. (1965) formulated the size-order principle, which is based on findings of a relation between motoneuron size and excitability in cats. These findings imply that the MUs are recruited and de-recruited in a size-ordered manner with low threshold MUs (small MUs containing mainly type I muscle fibres) recruited first and de-recruited last during a period of muscle contraction (Hägg, 1991; Bear et al., 2001). This is exemplified in Figure 5.

Based on the principle of size-ordered MU recruitment, the Cinderella hypothesis (Hägg, 1991) postulates that some of the low threshold MUs will thus be overused if the contraction is sustained too long without periods of total relaxation. This overuse would then cause selective muscle fibre injuries, which in turn would produce muscular disorders, e.g. myalgia. These assumptions are supported by studies showing type I muscle cell morphology changes (Larsson et al., 1988; Kadi et al., 1998b) and impaired microcirculation of blood through specific muscle fibres (Lindman, 1992; Larsson et al., 1998; 1999; 2001b) in myalgic trapezius muscle tissues. Other studies showed significant differences between subjects with different work tasks (Kadi et al., 1998a; Larsson et al., 2001a) and between tender/no tender points (Larsson et al., 2000), but not between...
muscles with and without myalgia. There are also indications, based on biopsies from the extensor carpi radialis brevis muscle, that forearm muscle abnormalities are significantly more common in patients than in healthy controls (Ljung et al., 1999). However, these muscle tissues showed different morphological abnormalities as compared to the trapezius muscle.

Hägg (2000) reviewed morphological studies. The question of whether and in which way myalgic muscles undergo morphological changes has not been fully answered and their relationship with pain perception also remains unclear. Nevertheless, these questions will not be further investigated in this thesis.

1.5 Studies regarding the Cinderella hypothesis in the context of computer work

The validity of the Cinderella hypothesis requires that the same MUs can be activated during variable loads related to ordinary computer work, such as mouse work, keyboard work, different body postures, during upper limb motions, and during psychological stress. Previous studies have shown that the same low threshold MUs can be active in the trapezius muscle in a wide range of different static arm positions (Kadefors et al., 1999), during a wide range of shoulder abduction movements as well as in computer mouse precision work, and during psychological stress induced contractions (Forsman et al., 2000; 2001; Lundberg et al., 2002). Søgaard et al. (2001) found that the same low level MUs in the EDC muscle were active during various right hand finger movement tasks that simulated computer mouse tasks. It has also been found that the same MUs in the biceps muscle could be recognised in both concentric and eccentric movements (Søgaard et al., 1998).

The validity of the Cinderella hypothesis also depends on the existence of MUs that can be exposed to a prolonged activity. This aspect has as yet been less investigated, and previous research focuses chiefly on the trapezius muscle. In a study of a 10-min attention demanding computer work task, six out of 38 recordings showed one or more MUs to be active throughout the whole work task (Waersted et al., 1996). In another study of 10-min low level muscle work tasks, some low threshold MUs were continuously active while others showed periods of inactivity in combination with direct recruitment of MUs of higher thresholds (Westgaard and De Luca, 1999). This phenomenon is called MU substitution, or rotation, and has also been reported in an
investigation of biceps brachii muscle activity during a prolonged, isometric elbow flexion of 10% of maximal voluntary contraction, MVC (Fallentin et al., 1993). A study of long term computer mouse work recently showed that some low threshold MUs may stay active at least as long as during the full session length (30 minutes), while others showed an on/off behaviour during the work task (Zennaro et al., 2002a).

How long are these MUs able to stay active? It has been reported that subjects have been able to deliberately keep one MU active for up to three hours and 17 minutes during voluntary muscle contractions (Stålberg, 1966). That study used biofeedback, not present in a normal working environment, to facilitate stable MU activity. It is thus not obvious that Stålberg’s results are valid in the context of a normal work task. Olsen et al. (2001) studied the impact of fatigue on MU activity during a sustained low force contraction until exhaustion in the right extensor carpi radialis (ECR) muscle. It was found that the majority of the MUs identified were active throughout the experiment, in spite of several indications of muscle fatigue, such as perceived exertion by the subject, significantly increased RMS values of surface EMG (SEMG) signals, and decreased mean power frequency (MPF). Furthermore, a comparison of MU activity in the extensor carpi ulnaris (ECU) muscle with and without experimental pain (by injection of hypertonic saline into the muscle) during a low level ramp contraction showed no effect on MU properties, such as number of MUs recruited, mean firing rate or MUAP amplitude and duration (Birch et al., 2000a). Neither were any pain modulation effects seen for the ECU, trapezius or flexor carpi radialis (FCR) SEMG levels during high precision use of a computer mouse, while experimental pain decreased the ECU SEMG activity in the highest activity phases during low precision mouse work (Birch et al., 2000b). Madeleine et al. (1998; 1999) found that this type of experimental pain entails similar sensory manifestations and motor coordination strategies as clinical work related neck-shoulder pain. Together these findings indicate that MU activity may stay constant for a long period of time, even after fatigue and/or muscle pain has occurred, especially if there is a high demand for the precision in the work.

1.6 Disorders with similar symptoms as myalgia

This section briefly describes some work related pain syndromes with symptoms similar to those of muscle pain, myalgia. The etiology and injury mechanisms of these syndromes are however not further investigated here.

Pain can be grouped into nociceptive, neurological and idiopathic pain, depending on its origin (Hauffman, 1999). Nociceptive pain originates from stimulation of pain receptors, nociceptors, by the presence of e.g. trauma, inflammation or lack of oxygen. Tendinitis and bursitis are common causes to nociceptive pain. Myalgia often has its origin in nociceptive pain and can be amplified by different surrounding factors and personal situations (Hauffman, 1999). Neurogenic pain is caused by pressure on nerves resulting from entrapment in surrounding tissues, e.g. blood vessels and bones. One common example here is the carpal tunnel syndrome. The third type is idiopathic pain, which is caused by unknown reasons but is nevertheless real for the patient. Primary fibromyalgia is one example of an idiopathic disorder.
1.6.1 Fibromyalgia

Primary fibromyalgia is characterised by widespread aches and pains, stiffness and sensations of general fatigue (Krsnich-Sriwise, 1997). The etiology of primary fibromyalgia is unknown and it is often referred to as nonarticular or psychogenic rheumatism. In the United States, 3-6 million people and 15-20% of the rheumatic patients may have fibromyalgia (Krsnich-Sriwise, 1997). Primary fibromyalgia is not considered to be a work related syndrome since trauma-induced pain, e.g. myalgia, is excluded as a primary cause (Hagberg, 1996a). Secondary fibromyalgia, however, may arise as a result of a chronic pain syndrome. For example, a prolonged pain experience may change the central nervous system’s (CNS) interpretation of muscle spindle signals into indications of pain, i.e. a “memorisation” of the pain (Hagberg, 1996b).

1.6.2 Tendinitis

Tendinitis is an inflammation of tendon tissues. Shoulder and elbow tendinitis are common pain syndromes (Burgess, 1991; Styf et al., 2001). Lateral epicondylitis, more popularly called tennis elbow, is the most common elbow tendinitis. Age alterations, microorganisms, mechanical influences or immunological reactions can cause tendinitis (Styf et al., 2001). There are indications, however, that the hampered muscular performance in patients with lateral epicondylitis is also due to physical muscle degenerations (Ljung et al., 1999). Thus myalgia may also be present in people suffering from epicondylitis.

1.6.3 Bursitis

The bursas are associated to the joints and serve as protection for the tendons against pressure forces from surrounding skeletal tissues and facilitate the movements of the tendons (Elfström, 1987). In bursitis, the bursa becomes inflamed and filled with fluid. This often causes, especially when the bursa becomes infected, tenderness in and around the bursa and restricted motion of the joint (Burgess, 1991).

1.6.4 Neural entrapments

A common disorder in this group is the carpal tunnel syndrome (CTS), which is caused by median nerve compression at the wrist. The CTS is believed to be an increasing problem among workers with repetitive wrist and finger motions (Mosely et al., 1991), e.g. computer mouse users, and often shows a chronical behaviour. Several studies have reported that, e.g., non-normal wrist positions and a high extent of repetitiveness are correlated to an increase in the risk of CTS development (Vingård et al., 2001).

1.7 Aim of this thesis

The aim of this thesis was to examine activation patterns in one shoulder and one forearm muscle during simulated computer work tasks in order to investigate whether the Cinderella hypothesis can explain the development of myalgia among computer users.
2 Methods and materials

This chapter presents the methods and materials used and common for Paper I, II and/or III. Information specific to one particular paper is given in Chapter 3, Summary of papers.

2.1 Subjects

In all of the studies (Papers I-III), none of the subjects had a history of shoulder/neck chronic pain and all were right handed. The Research Ethics Committee of Gothenburg University approved the studies, and all subjects were fully informed about the experimental procedures before giving their consent.

2.2 Electromyography

Intramuscular EMG methods were chosen to detect MU activity patterns, and surface EMG techniques were chosen to obtain a measure of overall activity levels in the muscles studied.

In the intramuscular EMG, a quadrifilar wire electrode was made using four 0.07 mm Teflon® isolated stainless steel wires, with an exposure of 0.3 mm at the tip, twisted together and inserted in a 0.9-mm hypodermic needle. The wire endings were cut in pairs, twisted, and bent around the needle tip, leaving one pair at a 1.0 mm and the other at a 1.5 mm distance from the needle outlet. The needle was chemically sterilised by spiritus dilitus (70%) and inserted into the right trapezius muscle, 20 mm medially from the midpoint of the line between the lumbar processus of the seventh cervical vertebra and the acromion (Papers I and III). In the right EDC muscle, the wire electrodes were inserted at one-third of the distance from the lateral epicondyle to the lateral styloid processus (Paper II). The insertion depth was 20-30 mm and the insertion angle 30 degrees from the skin surface, i.e. an insertion depth of 10-15 mm normal to the skin surface. The needle was then removed, leaving the wires inside the muscle. One of the four wires served as a common electrode. There were three electrode pairs, and three channels of bipolar intramuscular EMG could be recorded.

Bipolar surface EMG was measured by two silver/silver chloride electrodes (N-00-S Blue Sensor, Medicotest, Denmark) placed on each side of the insertion point at an inter-electrode distance of 20 mm. One ground electrode was placed on the skin on the lumbar processus of the seventh cervical vertebra (Papers I and III) and another on the lateral styloid processus (Paper II).

Both surface and intramuscular EMG signals were low pass filtered with a cut-off frequency of 8 kHz, sampled with 20 kHz and stored on a computer hard disk.

2.3 Decomposition and classification

A semi-automatic program was used for the MUAP decomposition and classification (Papers I-II). The program was an improved version of a previously used program based on MATLAB® (Forsman et al., 1999; 2001). The improvement included template updating; an unclassified segment was compared to templates built on the MUAPs in a time window, typically set to ±3 s. This made it possible to improve the recognition of the MUAPs in long term measurements.
Three intramuscular EMG channels, time locked to each other and band pass filtered, were used for classification. Periods during which the average amplitudes of the signals exceeded, e.g., four times the noise levels were identified as active segments. The duration of a segment ended (in both directions) where the amplitude fell below, e.g., two times the noise level. The limits, here exemplified as 4 and 2, were adjusted in order to include segments of MUAPs but to exclude segments containing merely noise. The equality, \( g \), between two MUAPs or a MUAP and a template was calculated as

\[
g = 1 - \frac{r^2}{s^2}
\]

where \( r^2 \) was the mean square residual, after time alignment, between the two segments and \( s \) was the RMS of the shorter of the two segments. Superpositions of two MUAPs were decomposed using the peel-off principle (Broman, 1988).

The program handled the stored data in 20-second periods, i.e. 180 periods for a 60-minute experiment. When the intramuscular recordings from the first period had been read, a classification of active segments into primary MU groups was made. The operator could in uncertain cases decide whether or not groups should be merged. When the next period had been decomposed in the same way, the resulting templates were compared to those from the last active seconds of the previous period. Again, the operator decided in uncertain cases whether or not templates originated from the same MU. The next period was then read, and the resulting templates were compared to those of the last updated templates of the MU groups identified so far. Any 20-second period could, after the automatic phase, be decomposed more accurately if so needed by using editing and manual clustering options (Forsman et al., 2001).

In the study reported in Paper III, a semi-automatic classification program, EMG-LODEC (Wellig, 2000; Zennaro et al., 2001), based on MATLAB®, was used to decompose the signal into MUAP trains. The program, developed by a research group at ETH in Zürich, was based on Wavelet transform algorithms. Each segment was transformed into a number of Wavelet parameters, and the segment could be classified according to the closest MUAP shape by comparison of the corresponding parameters for the segment and the MUAP shape. A software based on MATLAB® was developed and used to review the clustering results and to manually cluster MU groups that the EMG-LODEC software did not automatically cluster.

In all the studies reported, the criterion used for continuous firing was at least one identified firing in a two-second moving window, and the classification rate was defined as the percentage of segments that could be classified into a specific MU.

### 3 Summary of papers

#### 3.1 Paper I

The specific aim of this study was to increase knowledge of the low threshold MU firing patterns during long term, low level static contraction in the upper trapezius muscle and, especially, to identify whether there exist continuously active MUs during that time period.

Eight subjects, four males and four females, participated in the study. The mean ages in the males and females were 41 and 39 years, their mean weights 76 and 65 kg, and their mean heights 180 and 165 cm, respectively.
The subjects were asked to sit in an adjustable chair with the right shoulder abducted 30° in the frontal plane, upper arm flexed at 30° and elbow flexed at 45°. The chair and armrest were individually adjusted for each subject. The subjects were instructed to maintain constant activity in the trapezius muscle by keeping the 0.5-second SEMG RMS value stable at a level of approximately 5 %MVE while they performed a static isometric shoulder abduction of the upper arm. During the 60-minute experiment, RMS values of SEMG were fed back visually twice each second to the subjects via a plot on a computer screen. For normalisation purposes, the subjects performed maximal voluntary contractions at the end of the experiment.

One successful 60-min experimental period was carried out in each of the eight subjects. The intramuscular signals were however lost after 56 minutes in subject 8. The mean value of the SEMG 0.2-second RMS level was 5.0 %MVE (range: 4.2-6.1 %MVE), while the average coefficient of variation (CV), i.e. the average standard deviation divided by the mean SEMG RMS level, was 23% (range: 15-37%). All subjects perceived moderate exertion 30-45 minutes into the experiment but did not have difficulty completing the 60-minute work task. The mean power frequency (MPF) did not decrease significantly during the experiment.

 Altogether in the eight subjects, 108 different MUs (range: 10-19) were identified and tracked. The average classification rate was 86% (range: 77-96%). In all subjects, one or several initially silent MUs were active after a certain time while some other initially active MUs became silent, in spite of the maintained SEMG RMS level. This behaviour may indicate MU substitution. On the other hand, in three out of the eight subjects, MUs were identified that were continuously active throughout the 60-minute measurement with the exception of a few 1-3-second interruptions coinciding with SEMG dips in two of these subjects. The mean firing frequencies for the continuously active MUs were 7.1, 9.0 and 7.7 firings per second (FPS) for subjects 1-3, respectively.

### 3.2 Paper II

The purpose of this study was to characterise the firing behaviour of MUs in a forearm muscle (EDC) during a prolonged, static, low level contraction and wrist movements.

Eight subjects, six males and two females, participated in the study. The mean ages of males and females were 37 and 36 years, their mean weights 83 and 60 kg, and their mean heights 184 and 160 cm, respectively.

The subjects sat in an adjustable chair with the right shoulder abducted 25° and the elbow flexed at 60°. The chair and armrest/table were individually adjusted for each subject. The protocol included two main portions, first a 25-minute isometric contraction, followed by wrist movements. For normalisation purposes, the subject performed maximal voluntary contractions in the direction of wrist extension at the end of the experiment.

#### 3.2.1 Isometric contraction

The subject’s forearm was pronated 45° and supported by a horizontal armrest. The subject held a standard computer mouse (IntelliMouse, Microsoft Corp.) in his/her right hand, causing a wrist extension of approximately 15°. Before the long term measurement, the subject was asked to keep the fingers on the mouse without resting the hand on it, as though he/she were prepared to use it, and a 10-second RMS value of the SEMG signal was calculated. This value was then shown to the subject as a target in a graph on a computer screen where 0.5-second RMS values were also fed back to
the subject continuously. This feature assisted him/her in keeping the target level of activity throughout the 25-minute finger-wrist extension.

Seven out of eight subjects were able to control isometric contractions around the target level with relatively low variances. The mean CV of the SEMG (25 minutes of 0.2-second RMS values) in these seven subjects was 17%. The SEMG RMS of the eighth subject showed great fluctuation with a CV of 35%, and the subject was therefore excluded from further analyses. The mean values of the SEMG RMS ranged between 6.7 and 14 %MVE. The MPF did not decrease significantly during the session.

In total, 67 MUs (range: 2-24) were identified. The classification rate ranged between 81 and 94%. In subject 1, one MU was active throughout the 25-minute measurement, while the majority of the MUs were partially active over time, which may indicate MU substitution.

3.2.2 Wrist movements
The dynamic portion of the protocol included full range of motion wrist flexion/extensions and deviations. The flexion/extensions started in maximal voluntary hand flexion with the hand over the table edge. The subject was asked to move through the range of motion to maximal voluntary hand extension, pause for two seconds, and move back to full hand flexion. One movement cycle was completed in 20 seconds. In the wrist ulnar/radial deviation measurements, the subject was asked to move his/her hand holding a computer mouse, with the forearm in contact with the table. The hand movement started in maximal voluntary radial deviation and the subject was asked to move through the range of motion to maximal voluntary ulnar deviation, pause for two seconds, and move back to full radial deviation. One movement cycle was completed in 20 seconds. All 20-second tasks were performed twice with about two minutes of rest between each trial.

During the full range of motion of wrist ulnar-radial deviation, EDC muscle activity (RMS of the SEMG) ranged between 2.5 and 50 %MVE. The corresponding range of muscle activity during the flexions/extensions was 2.0-54 %MVE.

The intramuscular EMG signals were decomposed, and MUs in the EDC muscle were identified from the ulnar/radial deviation recordings, for all eight subjects. The signals of the flexion/extensions were more difficult to decompose because of many MUAP superpositions during the extension phase, and signals from only three subjects were successfully decomposed. For the ulnar/radial deviations, MUs with more than 10 FPS throughout the range of motion were observed in nine of the sixteen trials. MUs with more than 10 FPS throughout the range of flexion/extension motion were observed in all six trials that could be analysed.

3.3 Paper III
The purpose of this study was to analyse MU firing patterns in the upper trapezius muscle during a long term computer work task and, specifically, to investigate whether continuously active MUs could be found during such work.

Four subjects, two males and two females, participated in the study. The mean age was 39 (range: 32-47) years, mean weight 69 (range: 64-76) kg, and mean height 169 (range: 162-186) cm. All subjects were experienced computer users.

The subjects were asked to sit in an adjustable chair in front of a standard computer mouse (IntelliMouse, Microsoft Corp.), a standard Swedish “Qwerty” keyboard and a
14” computer flat-screen VDU. The chair, armrest and table were carefully adjusted for each subject individually in order to allow the subject to position his/her upper arms vertically and to obtain a 90º angle between the upper and lower arm if so wished by the subject. The positions of the mouse, keyboard and computer screen were chosen by the subjects according to their wishes. The subjects performed a 60-minute combined mouse and keyboard work task, which consisted of editing a text in which every 20th word was in boldface. The task was to (1) double click on the boldfaced word, (2) single click on the boldface icon (i.e. un-bold the word), and (3) retype the word, using the keyboard. No time pressure or demand for perfection was placed.

Subject 4 was excluded from the study due to the poor quality of the intramuscular EMG signals in this subject. The median SEMG levels for subjects 1-3 were 7.1, 14.1 and 3.3 %MVE, respectively. The average gap (a “gap” is defined here as an occasion on which the SEMG RMS level is below 1 %MVE for greater than 1/8 s) frequencies and the relative times during which SEMG <1 %MVE for subjects 1-2 were less than 1 min⁻¹ and 1 %, and 13 min⁻¹ and 13.4% for subject 3. It was observed from video recordings that subjects 1-2 lifted their shoulders during the keyboard input task, which may have induced periodical SEMG increases and less gaps and muscle rest.

The average classification rate of decomposed intramuscular EMG segments into one or several MUAPs was 87% for subject 2. Decomposition problems were experienced for subjects 1 and 3 due to external signal disturbances and too large electrode pick-up volumes. The classification rates for subjects 1 and 3 were thus only 59 and 42%, respectively. Classification results in subject 2 showed that 10 of 15 identified MUs were firing for >90% of the working time while only one was active for <70% of the working time. Subject 1 showed a somewhat lower degree of long term MU activity; among the 15 MUs identified, the activity percentage was >90% for five MUs and <70% for four MUs. In subject 3, none of the 12 MUs identified showed an activity percentage >90%, while six were active <70% of the working time. Low classification rates, as for subjects 1 and 3, induce a negative bias in the estimated amount of MU activity, which should be considered in interpreting the results.

4 Discussion

The results of the work described in this thesis show that there is a possibility for low threshold MUs to be continuously active during long term work tasks, such as in computer work, in both the trapezius muscle and in the EDC finger/wrist extensor muscle. There are also indications that not every low threshold MU necessarily follows this activity pattern. Instead, some MUs seem to show an on/off behaviour perhaps owing to MU substitution (inhibition of one MU followed by excitation of another). These findings are consistent with findings by Waersted et al. (1996), Zennaro et al. (2002), and Westgaard and De Luca (1999), with the exception that the latter study reported a more synchronised on/off behaviour in many of the non-continuously active MUs. Similar MU behaviour was reported by Fallentin et al. (1993).

Apart from these intra-individual differences in MU activity patterns, the results of this thesis also indicate inter-individual differences; some subjects showed continuously active MUs while others did not. This was also reported in a long term computer work study performed by Zennaro et al. (2002). In addition, there was a tendency for subjects who showed long term MU activity in one specific task (Paper I) to show this also in other tasks (Papers II and/or III). Two possible explanations may be either
different MU recruitment strategies between different human beings and/or different work strategies. An earlier study showed that same subject could, by training and EMG data feedback, perform the same work task at different trapezius muscle load levels (Palmerud et al., 1995). Due to the very restricted recording volume within the muscle, however, it is important to stress that the repeatability and reproducibility of the intramuscular EMG measurement method are most likely very low. These characteristics offer a third possible explanation for the inter-individual differences indicated here.

As mentioned in Chapter 1.4.3, there is still an uncertainty as to whether and in which ways painful muscle tissues undergo morphological changes. It is also unknown how long a continuous activity and what firing pattern may be needed for human skeletal muscle cells to become damaged. An animal study by Lexell et al. (1993) may provide some information. They studied the degeneration process in a rabbit muscle, the extensor digitorum longus, for nine days of continuous electrical stimulation with pulse trains in frequencies ranging from 1.25 Hz to 10 Hz. They found a significantly higher presence of degenerated muscle fibres at higher stimulation frequencies, and muscles exposed to 10 Hz intermittent stimulation (one hour on – one hour off -...) showed significantly less (but still significantly more than control) degeneration than muscles stimulated continuously with 5 Hz, i.e. where the same total number of impulses were delivered over the nine days. However, it is unclear whether these degenerations can be considered signs of the development of myalgia.

4.1 Protocols

The work tasks described in Papers I-II were highly simplified as compared to actual computer work. However, the major aim in these two studies was to investigate whether there is a possibility of the existence of continuously active MUs in the trapezius and EDC muscles even during simplified work tasks, chosen to be close to computer work. If so, the next step would naturally be to study MU firing patterns during a more realistic computer work task.

In Paper III, the subjects performed a standardised computer work task that contained a common operation used in the context of a text editing process. Naturally, computer terminal work contains a greater number of work tasks than the protocol described here. One single standardised work task was chosen, however, in order to reduce the number of variables. Furthermore, other studies have detected continuously active MUs during long term computer work tasks slightly different from those reported in Paper III, such as in a 10-min keyboarding task (Westgaard and De Luca, 1999) and a 30-min “click-and-drag” task using a computer mouse (Zennaro et al., 2002a).

The use of intramuscular measurements implies that the studies are preferably carried out in a laboratory environment. Two important reasons for this are the high sensitivity to signal disturbances and the need of a relatively sterile environment. Thus, we are forced to bring the subjects to a standardised environment that is new for them, rather than bring the measurements to the subject’s ordinary workplace, which in many cases would be more desirable. This may cause the subject to perform the work task differently than he/she would otherwise do, and may imply that the unfamiliar environment induces a certain psychological stress beyond that of the physical workload. However, the latter phenomena may not cause any significant measurement errors since there are studies that show that the same low threshold MUs can be found to be active both under psychological and physical workloads (Forsman et al., 2000;
Lundberg et al., 2002). It may be possible to introduce field studies for MU detection in the near future, if a currently studied signal processing technique using multi-array surface EMG electrodes (Disselhorst-Klug et al., 2000) succeeds as expected.

4.2 Electromyography

As mentioned in Chapter 1.2.2, EMG so far shows an advantage over MMG in terms of possibilities for high spatial resolution, due to the relative simplicity of inserting EMG electrodes intramuscularly and thereby recording information from single MUs. Intramuscular EMG was therefore chosen for the detection of MU activity patterns. Wire electrodes were selected for that purpose, since they are suitable for studies of MU firing patterns during dynamic work tasks (see Chapter 1.2.1). The physical parameters for the intramuscular electrode (see Chapter 2.2) were chosen in order to obtain a low background noise level and an adequate amount of recorded muscle activities, with the objective of facilitating recordings of MUAP signals from several simultaneously active MUs and achieving high decomposition efficiency at the same time. Finally, surface EMG is at present one the most established and well-known techniques for recording overall muscle activity levels and was therefore chosen for that purpose.

Due to the very restricted recording volume, necessary to be able to decompose the intramuscular signals, there is a clear possibility of not finding any existing long term active MUs. This may affect the results in at least two important ways: (1) by underestimation of the number of subjects with long term active MUs and (2), by limited method repeatability and reproducibility. The latter makes it difficult to use the present method for comparisons between different groups, e.g. healthy subjects versus patients suffering from myalgia. However, neither of the two possible effects jeopardises the conclusions of this thesis since the main question was whether it is possible to find continuously active MUs during simulated computer work in healthy subjects, and not to compare different groups or quantify the number of continuously active MUs.

4.3 Decomposition and classification

A segmentation carried out with sections of variable length has the advantage of containing not too much and not too few data for classifying the segment and was therefore chosen as a segmentation technique in the work reported in this thesis. As mentioned in Chapter 1.3.3, both single-linkage and complete-linkage techniques for the classification of segments may have limitations in the context of decomposing EMG signals acquired from muscle contractions of a long duration. To solve this, we used a mixture of both methods. As in complete-linkage, we used templates, but these were based on the MUAP shapes from a time window, e.g. ±3 s, around a specific segment. The templates thus changed somewhat with time, a change that it was possible to edit after the complete classification to evaluate its correctness.

To evaluate the classification performance of a newly developed decomposition program and investigate whether it was less time consuming to use this, we used the EMG-LODEC software for decomposition in Paper III. We found that the latter program tended to produce somewhat lower classification rates and needed some extra improvements to its interface with the user to make it into a less time-consuming work tool than did the former program. With these improvements, however, the EMG-
LODEC software is judged to be a suitable alternative for long term recordings, especially when the classification rate levels are not exceptionally crucial.

As shown in the results, the classification rates of the segmented intramuscular signals were mainly between 85 and 95%. The aim of the thesis did not require 100% decomposition or an identification rate of 100%. An incomplete decomposition introduces a bias in e.g. the firing rate estimates, i.e. an underestimation of the MU activity, and this does not hazard the findings of long term, continuously active MUs during work tasks such as in computer work.

A more critical item is whether any misclassifications occurred in favour to some MUs in terms of the amount of activity. The probably safest way to avoid any such misclassifications is to manually examine the clusters of classified MUAP shapes for every MU throughout the full test sequence. If any suspected misclassifications have occurred, it is then better to reject than to accept the classification. However, this requires extremely extensive efforts when long term workloads are to be analysed. To achieve a reasonable analysis workload and still receive data satisfactorily examined for misclassifications, a number of time periods were chosen for each test sequence as random samples for manual analysis.

5 Conclusions and suggestions for future work

In conclusion, the results of this thesis show that there is a possibility for some low threshold MUs to be continuously active in the trapezius muscle and the EDC finger/wrist extensor muscle during long term work tasks, such as in computer work. These results support the Cinderella hypothesis on a selective overuse of specific low threshold MUs in the context of computer work. However, only a minority of the low threshold MUs showed extensive activity; many others were intermittently active, which may be a result of MU substitution. Moreover, the questions remain as to whether this extensive MU activity will result in the long run in damage to the muscle cells and how the pain generation process leading to myalgia functions.

It is important to stress that all studies presented in this thesis were done in a laboratory environment, which may cause the subject to perform the work task differently than he/she would do otherwise. A natural continuation in future work would thus be to make field investigations of MU firing behaviour among computer operators doing normal work tasks. To be able to do that, we plan to refine existing and develop new required hardware and software tools.

Moreover, we recommend studying groups with muscular complaints and compare them with healthy controls, in order if possible to investigate eventual inter-group differences in MU recruitment strategies. To our knowledge, this has been investigated to this time in only one recently performed study as a sub question and with a relatively small number of subjects (Zennaro et al., 2002b). The study reported indications of some inter-group differences, although not significant ones.

Finally, still open and important questions are how long a continuous activity or what firing pattern is needed for muscle cells to become damaged, and what is the pain generation process leading to myalgia. Research into these questions will require extensive cooperation with colleagues in the medical research areas.
References


Larsson, B., Björk, J., Kadi, F., Lindman, R., Gerdle, B., 2001b. Capillary supply and moth-eaten fibres in cleaners with and without work-related trapezius myalgia and in healthy control subjects. Submitted for publication.


