THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Muscular activity in light manual work

– with reference to the development of muscle pain among computer users

STEFAN THORN

Department of Product and Production Development
Production Systems
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2005

Arbetslivsinstitutet

This work was carried out at the National Institute for Working Life/West, Göteborg

Muscular activity in light manual work
– with reference to the development of muscle pain among computer users
STEFAN THORN

ISBN 91-7291-695-8

Doktorsavhandlingar vid
Chalmers tekniska högskola
Ny serie nr 2377
ISSN 0346-718X

Front cover:
”Shoulder pain” by Keith Brofsky

Published and distributed by:
Department of Product and Production Development
Chalmers University of Technology
SE-412 96 Göteborg, Sweden
Telephone +46 (0)31 772 1000

Printed in Sweden by:
Chalmers Reproservice
Göteborg 2005

Muscular activity in light manual work
– with reference to the development of muscle pain among computer users

STEFAN THORN

Department of Product and Production Development
Production Systems
Chalmers University of Technology

Abstract

Work related musculoskeletal disorders (WMSDs) in the neck/shoulder area and the upper extremities are common among computer users, despite the relatively low muscle load levels involved. Muscle pain (myalgia), primarily experienced in the neck/shoulder area, is a frequent type of WMSD. The Cinderella hypothesis postulates that groups of muscle fibres (motor units, MUs) are continuously active during monotonous workloads, leading to MU overuse and myalgia.

The main scope of this thesis was to investigate whether muscular activity patterns during computer work are consistent with the Cinderella hypothesis on selective MU overuse. In three studies, MU activity patterns were registered by intramuscular wire electromyography (EMG) in the upper trapezius (N=8 and N=4, respectively) muscle and the extensor digitorum communis (EDC) muscle (N=8) during prolonged (25-60 minutes) and short-term (20 seconds) work tasks characterising computer work. Surface EMG (SEMG) techniques were chosen to measure the overall activity in the muscles studied. In a study of 79 elderly female computer users with vs. without neck/shoulder complaints (cases/non-cases), SEMG was recorded bilaterally in the upper trapezius muscles during a type, edit, precision and colour word stress computer task (task length 2-5 minutes). Median and 10th percentile SEMG root mean square (RMS) levels and relative muscle rest time (RRT) was compared in cases vs. non-cases. For 11 subjects performing 60 minutes of computer work, median and 90th percentile SEMG RMS levels were compared for the upper trapezius, EDC and flexor carpi ulnaris (FCU) muscles during single vs. double mouse clicks. In addition, EDC MU activity was detected in three of the subjects during 50 consecutive mouse clicks.

Continuously active MUs were found both in the upper trapezius and in the EDC muscles during the prolonged and short-term low-level work tasks investigated, although a majority of the MUs were intermittently active. During the stress task (but not during the typing, editing or precision mouse work tasks), decreased trapezius muscle rest was indicated for cases compared to non-cases. These findings give support to the Cinderella hypothesis on an MU activity-based development of myalgia in the context of computer work and indicate that stressful working conditions increase the risk for muscular overuse. No support was found for double clicking a computer mouse constituting a higher risk for MU double firings (doublets) and WMSDs than single clicking. Further investigations are needed of the underlying mechanisms of MU substitution and inter-individual MU activity differences, and of the causal pathways between continuous and sustained MU activity, selective MU overuse and chronic pain.

Keywords: computer work, myalgia, Cinderella hypothesis, intramuscular electromyography, motor units, doublets, muscle rest, 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.

I Thorn S, Forsman M, Zhang Q, Taoda K (2002) Low-threshold motor unit activity during a 1-h static contraction in the trapezius muscle. Int J Ind Ergonom, 30(4-5): 225-236

II Forsman M, Taoda K, Thorn S, Zhang Q (2002) Motor-unit recruitment during long-term isometric and wrist motion contractions: a study concerning muscular pain development in computer operators. Int J Ind Ergonom, 30(4-5): 237-250

III Thorn S, Forsman M, Zhang Q, Hallbeck S (2002) Motor unit firing pattern in the trapezius muscle during long-term computer work. In: Kollmitzer J and Bijak M (eds.), Standardization for a Better Exchange of Ideas, Proceedings of the 16th Congress of the International Society of Electrophysiology and Kinesiology, Vienna, pp. 34-35

IV Thorn S, Forsman M, Hallbeck S (2005) A comparison of muscular activity during single and double mouse clicks. Eur J Appl Physiol, 94(1-2): 158-167

V Thorn S, Søgaard K, Kallenberg LAC, Sandsjö L, Sjøgaard G, Hermens HJ, Kadefors R, Forsman M (2005) Trapezius muscle rest time during standardised computer work - a comparison of elderly female computer users with and without self-reported neck/shoulder complaints. Submitted

Contribution to listed papers

The following table illustrates the contributions by Stefan Thorn to the papers listed above.

	Paper				
	I	II	III	IV	V
Idea, formulation of study	2	2	3	3	3
Choice of techniques and experimental design	2	2	3	3	1
Performance of experiments	3	3	3	3	1
Analysis of experimental results	3	1	3	3	3
Data processing and statistics	3	2	3	3	3
Writing of manuscript	3	2	3	3	3

3 = Main responsibility
2 = Contributed to a high extent
1 = Contributed

”All generalisations are dangerous, even this one”

Alexandre Dumas

Acknowledgements

This work received financial support from the Swedish Council for Working Life and Social Research (FAS), which is gratefully acknowledged.

I would like to take the opportunity to thank a number of people whose help and support has been essential for the realisation of this work.

My supervisor, Mikael Forsman, for your outstanding engagement and personal concern in my research work and my general well being. I have truly enjoyed our co-work. Many thanks also to my assistant supervisor, Roland Kadefors, for your assistance and our fruitful discussions during the writing phases of this thesis.

My co-authors for all your support and for helping me broaden my perspective of my field of research. I would also like to thank Gunilla Zachau for invaluable analysis support.

My dear friend and colleague, Leif Sandsjö, for support, inspiration and many laughs both at work and "out there in the real world". Music, maestro!

My PhD student companions, both present and former, I will truly miss you all. Thanks also to my colleagues at the National Institute for Working Life, for creating a stimulating environment and for all the fun activities after work.

A special thanks to those closest to me: my family and friends. You are everything that really matters.

Stefan Thorn

Göteborg, November 2005

List of abbreviations

ATP	Adenosine triphosphate
CAD	Computer-aided design
CNS	Central nervous system
CV	Coefficient of variation; standard deviation normalised by mean
ECU	Extensor carpi ulnaris muscle
EDC	Extensor digitorum communis muscle
EMG	Electromyography
EVA	Exposure variation analysis
FCR	Flexor carpi radialis muscle
FCU	Flexor carpi ulnaris muscle
IED	Inter-electrode distance
MMG	Mechanomyography
MPF	Mean power frequency
MSA	Muscle spindle afferents
MU	Motor unit
MUAP	Motor unit action potential
MVC	Maximal voluntary contraction
MVE	Maximal voluntary electrical activity
NMQ	Standardised Nordic musculoskeletal questionnaire
p10	10th percentile (of SEMG RMS)
p90	90th percentile (of SEMG RMS)
RMS	Root mean square
RRT	Relative muscle rest time
RVC	Reference voluntary contraction
RVE	Reference voluntary electrical activity
SEMG	Surface electromyography
SD	Standard deviation
TNS	Tension neck syndrome
VDU	Visual display unit
WMSD	Work related musculoskeletal disorder

Table of Contents

1 Introduction 1
  1.1 Computer work and muscular disorders 1
  1.2 Basic muscle physiology 2
  1.3 Proposed pathomechanisms of muscle pain 3
  1.4 Methods for measurement of muscular activity 8
  1.5 Signal processing of electromyography data 9
  1.6 Muscle activity patterns – previous results 12
  1.7 Aims of this thesis 16
2 Methods and materials 17
  2.1 Subjects 17
  2.2 Electromyography 17
  2.3 Goniometry 19
  2.4 Mouse force 20
  2.5 Questionnaires 20
  2.6 Signal processing 20
  2.7 Statistics 22
3 Summary of papers 23
  3.1 Paper I 23
  3.2 Paper II 24
  3.3 Paper III 25
  3.4 Paper IV 26
  3.5 Paper V 27
4 Discussion 29
  4.1 Continuous vs. intermittent motor unit activity 29
  4.2 Motor unit doublets 30
  4.3 Lack of muscle rest 31
  4.4 Methodological considerations 32
  4.5 Morphological changes and pain generation 38
5 Conclusions 41
6 Further research 43
References 45

1 Introduction

1.1 Computer work and muscular disorders

Work related musculoskeletal disorders (WMSDs) in the neck/shoulder region and the upper extremities are common and increasing among computer operators in Sweden, especially women (Wigaeus Tornqvist et al. 2000; Hagman et al. 2001; SCB 2005). The use of computers at work has increased substantially in the last decade (Wigaeus Tornqvist et al. 2000; SCB 2003), and several studies report augmented problems with increased computer usage (Wigaeus Tornqvist et al. 2000; Fogleman and Lewis 2002; Blatter and Bongers 2002; Jensen 2003).

WMSDs referred by self-reported discomforts and disabilities have generally shown a higher prevalence among computer users than diagnoses from clinical examinations, although a variety of clinical signs have been found (Juul-Kristensen et al. 2005). With respect to the neck/shoulder region, a marked part of the clinical signs and symptoms can be referred to as muscular disorders, such as muscle pain (myalgia) and tension neck syndrome (TNS). Juul-Kristensen et al. (2005) reported that trapezius myalgia and TNS were the two most frequent clinical diagnoses among elderly female computer users with self-reported neck/shoulder complaints. Moreover, an extensive review study of epidemiological findings (Bernard et al. 1997) inferred consistently high odds ratios for TNS associated with static postures or static loads. For the upper extremities, muscular complaints and disorders are generally less frequently reported. In physical examinations of female workers in highly repetitive industries, however, it was found that muscle pain and tenderness was the greatest problem – not only in the neck/shoulder region but also in the forearm/hand region (Ranney et al. 1995). Furthermore, they reported that the majority of the muscular disorders in the neck/shoulder and forearm/hand regions were located in the trapezius and forearm extensor muscles, respectively.

Computer work tasks often contain a high degree of monotony. For instance, 47% of the male and 67% of the female office employees working more than half of their work hours in front of a visual display unit (VDU) have reported monotonous text editing and data entering as their main work tasks (Wigaeus Tornqvist et al. 2000). Muscle loads in the neck/shoulder area and the upper extremities are normally relatively low and static during computer work. For instance, in field studies of computer-aided design (CAD) operators, it was demonstrated that the median muscle activity was approximately 4% of the maximal voluntary electrical (MVE) activity on the dominant side of the upper trapezius muscle (Jensen et al. 1998, 1999). Exposure variation analyses (EVAs) in that 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 indicates a high degree of static behaviour. For the upper extremities, median muscle activities of approximately 6 %MVE during CAD work (Jensen et al. 1998), 8-10 %MVE during various pre-defined mouse work tasks (Laursen et al. 2001) and 17 %MVE during high-precision work (Aarås and Ro 1997) have been reported in the extensor digitorum communis (EDC) muscle. The corresponding 10th percentile (p10) EDC muscle activities were in these three studies measured to be approximately 2.5, 5-6 and 11 %MVE, respectively, indicating static behaviour in the EDC muscle as well during computer work.

The physiological mechanisms for the development of myalgia caused by low-level, prolonged monotonous workloads, such as in computer work, are not fully understood. A better understanding is essential to producing scientifically well-founded work organisational recommendations and treating patients with muscle disorders effectively.

Even if a notable part of the clinical signs and symptoms of especially neck/shoulder WMSDs can be referred to as muscular disorders, many disorders are not primarily related to the muscle tissues. Since the scope of this thesis is limited to the context of muscle pain, however, the pathogeneses of non-muscular disorders are not further elaborated here.

1.2 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.

1.2.1 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 impulses 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 an 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 of very small MUs, i.e. few muscle fibres. Larger muscles with lower fine-control requirements, e.g. the shoulder muscles, contain, on average, larger MUs with many muscle fibres. The total muscle force produced depends on the numbers of MUs activated, the sizes of the MUs and fibres activated and the stimulation frequency of each MU.

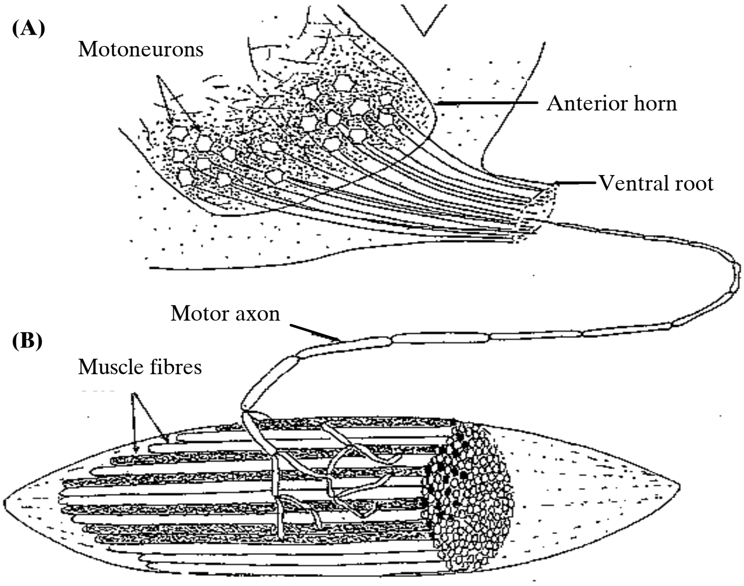

Figure 1. Organisation of the skeletal muscle. The figure shows the innervation between the spinal cord ventral root (A) and the muscle (B). Darkened fibres together with the motor axon describe one MU. Reprinted with permission of McComas (1996).

1.2.2 The muscle fibre impulse train

When a muscle fibre is stimulated into contraction, a train of electrical impulses is distributed from the innervation zone in both directions to the fibre endings. Each impulse 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 (Figure 2). Because of the so-called absolute refractory period, the fibre cannot be triggered to contract within shorter intervals than approximately one millisecond, i.e. a theoretical maximum stimulation frequency of 1000 Hz. Normally, the stimulation frequency is however much lower; typically 10-20 Hz for slow, low-threshold MUs and with occasional bursts of 30-60 Hz for fast MUs of higher threshold (Bear et al. 2001).

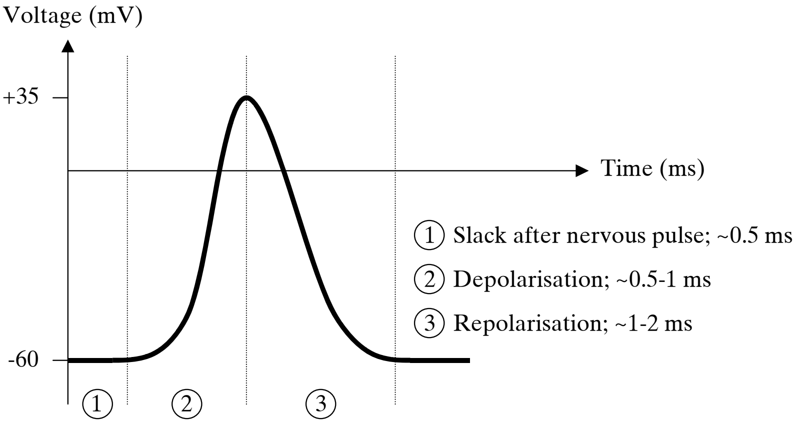

Figure 2. Electrical impulse from one muscle fibre (schematic figure).

1.3 Proposed pathomechanisms of muscle pain

As mentioned, the mechanisms for the development of myalgia caused by monotonous, low-level workloads, such as in computer work, are not fully understood. For prolonged workloads at higher contraction levels, hampered blood macrocirculation due to increased intramuscular pressure has generally been considered an important risk factor for muscular pain; an increased intramuscular pressure may 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. In muscles located deep in the body, particularly when surrounded by rigid anatomical structures, this may also be a possible risk factor in low-level workloads. However, this is unlikely to occur in superficial muscles such as the trapezius muscle, and potentially also the EDC muscle, since the intramuscular pressure loads measured during low-level work tasks (Järvholm et al. 1991) are generally low enough to allow muscle fatigue recovery (Körner et al. 1984).

Several other hypotheses are instead discussed in the case of low-level workloads. This chapter briefly describes some of them. The main emphasis is on the Cinderella hypothesis, the one investigated and studied in this thesis. Apart from the blood vessel-nociceptor interaction hypothesis and the hyperventilation theory, most of the hypotheses about muscle pain development are based on the pain originating at the muscle cell level.

1.3.1 The blood vessel-nociceptor interaction hypothesis

This hypothesis, formulated by Knardahl (2002), postulates that the pain originates from nociceptive[1] interactions in the connective blood vessels that supply the muscle fibres. Three potential mechanisms in this interaction are mentioned: (1) extension of blood vessels (vasodilatation), (2) vascular production of pain producing substances, e.g. prostaglandins and nitric oxide[2], and (3) blood vessel inflammation. The two latter mechanisms have, at the present, not been further developed by Knardahl. As concerns the nociceptive effect of blood vessel extension, Knardahl refers to a well-known association between vasodilatation and pain in migraine patients and to the pain effect of different vasodilatating drugs. Animal studies have shown a response of vasodilatation in the skeletal muscle during active cognitive work (Knardahl and Hendley 1990), which should support the blood vessel-nociceptor interaction hypothesis in the context of cognitive work tasks (Knardahl 2002).

The mechanisms mentioned in this hypothesis might all be plausible causes for the development of muscle pain. Both the mechanisms and the possible nociceptive interactions need to be further elaborated, however, as do their associations with pain development. It is not obvious, for instance, whether vasodilatation is the cause or the effect of pain. Furthermore, increased cognitive demands and other psychological stressors generally excite sympathetic nerve activity. In humans, the existence of sympathetic vasodilatation is still doubtful (Joyner and Dietz 2003). Instead, increased sympathetic nerve activity normally leads to a contraction of the arterial blood vessels (vasoconstriction) (Bear et al. 2001; Hansen 2002), i.e. the opposite of vasodilatation.

---

[1] Pain originating from stimulation of pain receptors (nociceptors).

[2] See also Chapter 1.3.4.

1.3.2 The hyperventilation theory

Schleifer et al. (2002) has developed a hyperventilation theory of job stress and WMSDs. This theory is based on a well-known relationship between severe stress and hyperventilation, which causes an acute drop in arterial CO_2. Previous studies have found lower end-tidal CO_2, compared to baseline, during sustained, repetitive computer work (Schleifer and Ley 1994a), where there was discrimination between high and low mental demands (Schleifer and Ley, 1994b). A drop in arterial CO_2 causes a decrease in carbonic acid in the blood. According to the hyperventilation theory, this results in respiratory alkalosis, i.e. a rise in plasma pH above 7.45 (Schleifer et al. 2002). This disruption in acid-base equilibrium will then in turn trigger a neuronal excitation, causing increased muscle tension and muscle spasms, with adverse effects for muscle tissue health.

This theory may serve as a relevant explanation for, or contribute to, the underlying mechanisms for muscle pain in the context of computer work, especially under stressful conditions. The proposed relationship between the verified drop in arterial CO_2 during normal working conditions and a neuronal excitation has, however, not yet been investigated.

1.3.3 The vicious circle hypothesis

Johansson and Sojka (1991) formulated a hypothesis describing the genesis and spread of muscular tension in patients with musculoskeletal pain syndromes. This model has recently been further developed by Johansson (2002) and Bergenheim (2003). The model works as follows: repetitive, static muscle contractions (in primary muscles) cause production of metabolites, which activates gamma-motoneurons projecting to both primary and secondary muscles. This activation increases the static and dynamic stretch sensitivity and discharges of primary and secondary muscle spindle[3] afferents[4] (MSA). First, the increased primary and secondary MSA activities will increase the reflex-mediated component of the muscle stiffness, which in turn causes a further production of metabolites in primary and secondary muscles. Second, an increased primary MSA activity will hamper proprioception[5], which could possibly lead to increased co-contractions. The result is a vicious circle that spreads and increases the sensations of pain throughout a body region. An increased sympathetic nerve activity, due to e.g. psychological stressors, may have an additional effect on proprioceptive control, although this still remains unclear (Passatore and Roatta, 2003) and has been contradicted by Matre and Knardahl (2003). Several animal studies show a metabolite-evoked increase of MSA activity (Pedersen et al. 1997; Wenngren et al. 1998), supporting the theory of increased muscle stiffness and reduced proprioceptive control. In humans, increased muscle fatigue (Pedersen et al. 1999) and metabolites (weak indications) (Rossi et al. 2003) have been shown to hamper proprioception. A review of articles on motor function under conditions of pain concluded that the activity in both painful and healthy agonist muscles is often reduced and the activity of the antagonist is slightly increased by pain (Lund and Donga 1991). Such behaviour has been reported in lower leg muscles

---

[3] A mechanoreceptor, sensitive to muscle length and changes in muscle length.

[4] Outgoing nerve (from the muscle to the spinal cord).

[5] Sense of body position and movement in space.

as an effect of experimentally evoked muscle pain (Graven-Nielsen et al. 1997). As a consequence of these changes, force production and the range and velocity of movements of the affected body parts are often reduced. The model by Lund and Donga is called the pain adaptation model, and may at first glance contradict the vicious circle hypothesis. However, a second plausible consequence of this constrained behaviour is a small increase in resting and postural muscular activity in the affected body parts. This is supported by findings of upper trapezius activity in medical secretaries (Hägg and Åström 1997) and cashier workers (Sandsjö et al. 2000) with and without self-reported neck/shoulder complaints (cases vs. non-cases), where the cases indeed tended to carry out the tasks at lower average load levels as compared to non-cases, but with a significantly lower degree of muscle rest. Thus, the vicious circle hypothesis and the pain adaptation model may be considered rather as synergistic than contradictory theories.

1.3.4 The nitric oxide/oxygen ratio hypothesis

According to this hypothesis, neck myalgia is evoked when low-level contractions in the trapezius muscle are combined with psychological stress or prolonged head-down neck flexion at work (Eriksen 2004). Both psychological stress and prolonged head-down neck flexion may increase sympathetic nerve activity (Ray et al. 1997; Shortt and Ray 1997; Eriksen 2004). This leads to arterial vasoconstriction, causing reduced capillary flow and intracellular O_2 in the skeletal muscle (Bear et al. 2001; Hansen 2002). In contrast to workloads at median to high levels, results of the latter study indicate that the sympathetic vasoconstriction is preserved as long as the muscle activity is of low intensity. The vasoconstriction will also give reduced vascular removal of NO produced during the muscle fibre excitation-contraction process (Beckman and Koppenol 1996). Thus, a sharp rise in the NO/O_2 concentration will occur, affecting mitochondrial function (Moncada and Erusalimsky 2002). Via a resulting insufficiency of adenosine triphosphate (ATP), this would lead to an increased production and efflux of lactic acid into the connective tissues (Spriet et al. 2000; Juel 2001), causing myalgia.

This new hypothesis may have great potential to explain the physiological mechanisms of the development of muscle pain in computer workers. In contrast to the traditional theory on hampered blood macrocirculation, this hypothesis instead handles insufficient blood supply on an active muscle fibre level. Insufficient muscle fibre rest will intensify and speed up the described mechanisms for the development of myalgia. There may thus be a close connection between the theories in the nitric oxide/oxygen ratio hypothesis and the implications of the Cinderella hypothesis.

1.3.5 The Cinderella hypothesis

Henneman et al. (1965) is credited as having introduced the size-order principle. They based it on findings of a relation between motoneuron size and excitability in cats. It should however be mentioned that similar findings were reported almost 30 years earlier – and in humans – by Denny-Brown and Pennybacker (1938). The size-order principle states that MUs are recruited and de-recruited in a size-ordered manner with low-threshold MUs (small MUs containing primarily type I muscle fibres) recruited first and de-recruited last during a period of muscle contraction, see the example in Figure 3.

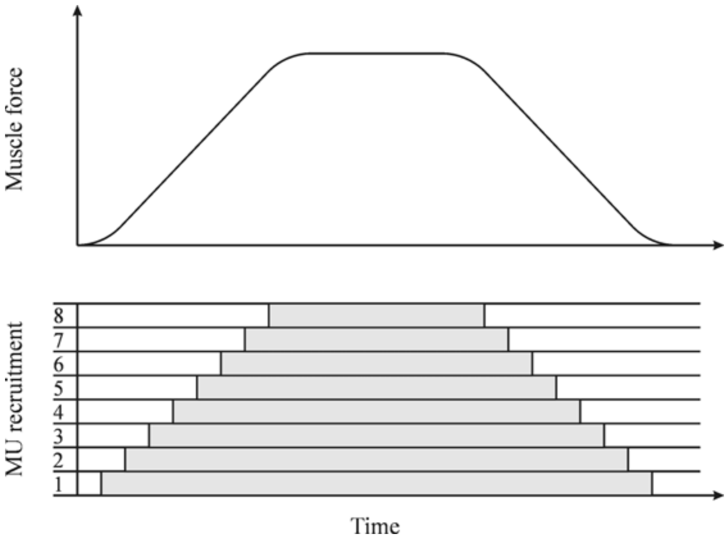

Figure 3. The size-ordered MU recruitment (schematic figure, after Hägg 1991).

Based on the principle of size-ordered MU recruitment, the Cinderella hypothesis (Hägg 1991) postulates that some of the low-threshold MUs will 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. It should be noted that a similar theory on selective MU fatigue, leading to localised metabolism disturbances and muscle pain, was earlier formulated by Hagberg (1981, 1982, 1984). The Cinderella hypothesis on MU over-usage is supported by studies showing type I muscle cell morphological 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, 2004) in myalgic trapezius muscle tissues. Other studies showed significant differences between subjects with different work tasks (Kadi et al. 1998a; Larsson et al. 2001) and between tender/no tender points (Larsson et al. 2000b), 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 than in the trapezius muscle.

Hägg (2000) reviewed morphological studies. Major findings in the subjects with myalgia were increased fibre cross-sectional areas, signs of mitochondrial disturbances in type I fibres and reduced capillarisation per normal fibre cross-sectional area (only found in women). With the exception of the findings of reduced capillarisation, similar findings have (less commonly) also been reported from work-exposed pain-free subjects, and their relationships with pain perception are unclear. The findings of mitochondrial disturbances and reduced capillarisation in women may however support the theory of localised ischemia, causing, via mitochondrial deficiencies leading to ATP insufficiency, lactic acid evoked muscle pain (see also Chapter 1.3.4). An insufficiency of ATP may also affect the homeostasis of Ca^{2+} released from the sarcoplasmic reticulum during the muscle fibre excitation-contraction phase (Sjøgaard and Søgaard 1998). Jackson et al. (1984) investigated the nature of the calcium-activated degenerative process that leads to skeletal muscle damage.

The perception of muscle fatigue is often considered a preventive strategy to avoid musculoskeletal overloading. Release of intracellular K^+ is one important feedback mechanism for fatigue (Sjøgaard and Søgaard 1998). At low-level workloads, the K^+ concentration is however maintained close to the resting level (Sjøgaard 1996). In the context of prolonged low-level work tasks, this implies an impaired ability to prevent overuse of low-threshold MUs, thus supporting the Cinderella hypothesis.

1.4 Methods for measurement of muscular activity

Several different methods are now used within ergonomic science to measure muscular activities during a work task. Two of them are electromyography and mechanomyography. Among other methods available are, e.g., measurements of intramuscular pressure changes, blood flow changes or tendon forces. These techniques are however not applicable for detection of MU firing patterns and will not be further discussed here.

1.4.1 Electromyography

The first logical deduction of muscle-generated electricity was documented by Italian Francesco Redi in 1666 (cited by Basmajian and De Luca 1985). By using electrodes placed on the skin surface, or inserted in the muscle, it is possible to record the electrical signals during muscle contractions (e.g.: Piper 1912). This well-established technique is called electromyography (EMG) and is often used for recording muscle activity in ergonomic studies (Kumar, 1996) and detecting signs of 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 1.2.2) and diffuse across the fibres via organic tissues. For a review of electromyographic techniques, see Basmajian and De Luca (1985).

EMG signals are often detected bipolarly, i.e. as the difference in electrical potentials between two recording points onto or inside the muscle. Bipolar configurations with surface EMG (SEMG) electrodes are used to record the electrical signals from larger parts of superficially situated muscles. An indwelling method, where the EMG signal is obtained by using a monopolar (i.e. only one) intramuscular electrode with a large contact area and a surface reference electrode, is common for more deeply located muscles. For the detection of activity in smaller parts of the muscle, bipolar indwelling configurations are often used. With a short inter-electrode distance between the two electrodes, this enables a high spatial resolution of the intramuscular EMG signal. This in turn makes it possible to record EMG pulses originating from single MUs, so-called MU action potentials (MUAPs; see Chapter 1.5.2). Weaker signals diffused from surrounding active muscle fibres are also recorded and create a background activity. 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 detecting MU firing patterns. When even shorter inter-electrode distances and smaller electrode contact areas are used, the recording volume of the bipolar intramuscular 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 limited possibility to detect firing patterns for more than one MU at a time. Detection of single fibre action potentials has been used to obtain single fibre properties under various conditions, e.g. propagation velocity (Stålberg 1966). If the inter-electrode distances and contact area of the electrodes instead are expanded, impulses from an increased number of muscle fibres will be detected by the bipolar EMG signal. Eventually the EMG signal will be too complex to decompose successfully, as the activity of too many different MUs will be detected at the same time.

Intramuscular EMG is detected either by wire or needle electrodes. When a muscular activity leads to a motion, the muscle is likely to move relative to the skin surface. Compared to needle electrodes, intramuscular wire electrodes can more easily follow these movements, retaining the position of the wires and thereby the electrode signal pick-up properties. Wire electrodes are therefore suitable for studies of MU firing patterns during motions. 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 is 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).

1.4.2 Mechanomyography

When a muscle contracts, the skin surface close to the muscle comes into vibration. 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 vibration by mounting 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. 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; Søgaard et al. 2003). Nevertheless, in terms of detecting MU firing patterns, EMG so far shows an advantage over MMG owing to the relative simplicity of mounting electrodes intramuscularly and thereby achieving a high spatial resolution of the signals.

1.5 Signal processing of electromyography data

1.5.1 Overall muscle activity

As mentioned above, overall muscle activity is generally detected from SEMG electrodes. The muscle activity level is predominantly calculated as the root mean square (RMS) of SEMG data. The RMS window length is often between 100 and 250 ms. The resulting $\mathrm{SEMG}_{\mathrm{rms}}$ curve represents the amount of measured muscle activity in µV as a function of time. In most cases, the $\mathrm{SEMG}_{\mathrm{rms}}$ is not presented in µV but in % of the SEMG activity during reference voluntary contractions (RVCs) or maximum voluntary contractions (MVCs). Recommended RVC and MVC protocols, and calculation techniques for the corresponding reference voluntary electrical (RVE) and maximum voluntary electrical (MVE) activities, have been reported by Mathiassen et al. (1995).

From the $SEMG_{rms}$ curves, the relative muscle rest time (RRT) can be calculated as the percentage of time with $SEMG_{rms}$ below a threshold level, defined as muscle rest (see example in Figure 4). The $SEMG_{rms}$ is in practice never zero, not even at total muscle relaxation, because of signal background noise. Often, the threshold level is instead set as a percentage of RVE or MVE. Related to RRT is the gap frequency, which is the average number of periods per minute with muscle rest. A muscle rest threshold level of 5 %RVE, or 1 %MVE, has been found to be appropriate in order to achieve a high sensitivity to differences between individuals (Hansson et al. 2000).

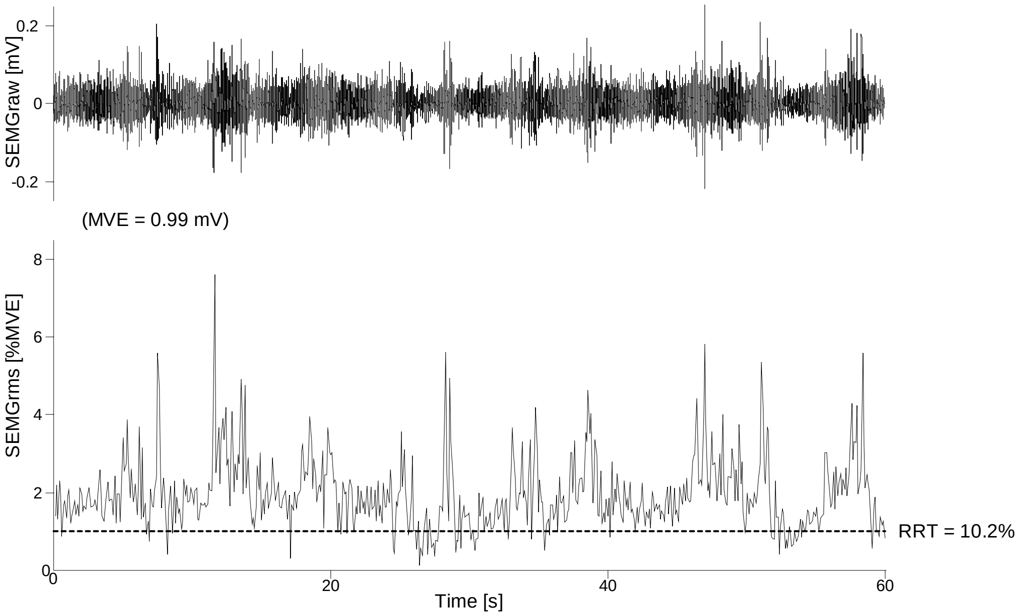

Figure 4. $SEMG_{rms}$ (lower curve; 100 ms RMS window) and RRT calculation (1 %MVE threshold level) from 60 s of trapezius SEMG raw data (upper curve), acquired during computer work.

1.5.2 Motor unit firing patterns

This chapter describes the basic methods for detecting MU firing patterns from intramuscular EMG data, i.e. signal decomposition (see example in Figure 5). Common to 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 MUAP signals, which are used as fingerprints for each recorded MU.

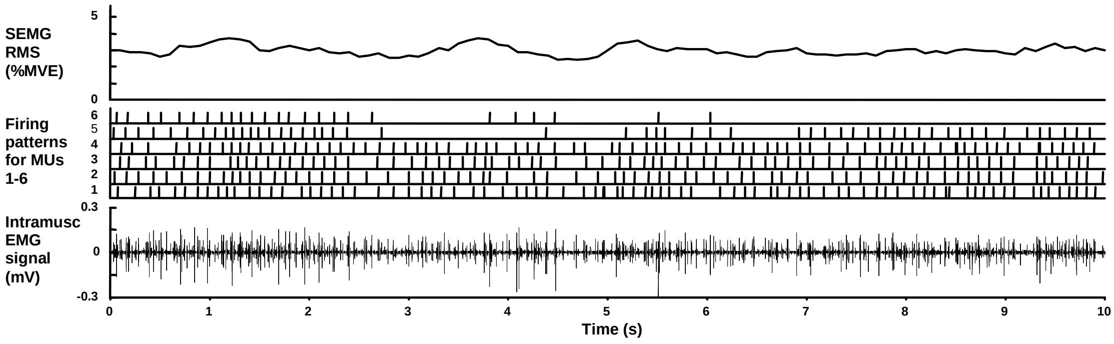

Figure 5. Firing patterns for six different MUs, detected by the decomposition of 10 seconds of intramuscular EMG data recorded from the right trapezius muscle during a computer work task. The SEMG RMS window is here 500 ms (courtesy of M. Forsman, National Institute for Working Life, Göteborg, Sweden).

As mentioned in Chapter 1.4.1, 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 an 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 principle 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, the MUAP (see examples in Figure 6). In order to maintain this shape throughout the work task, it is important that the electrodes do not move in relation to the muscle fibres.

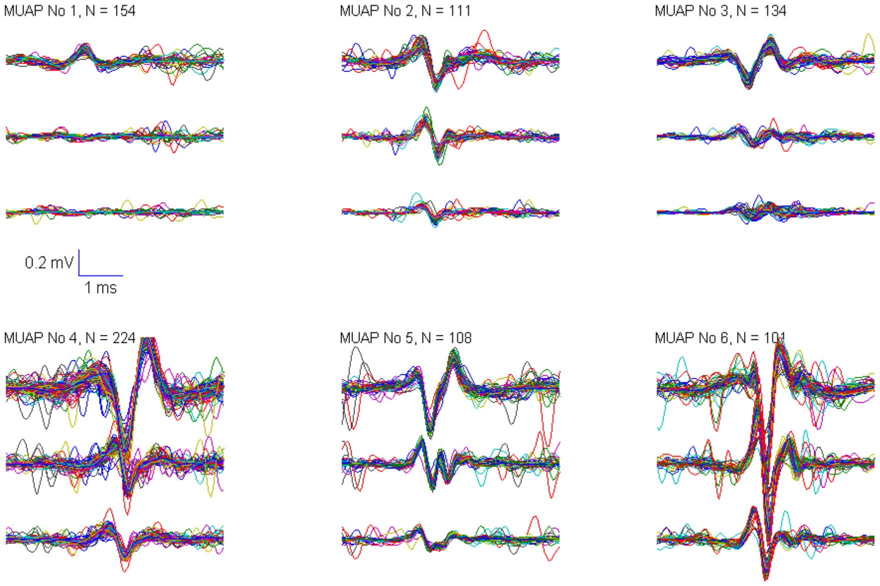

Figure 6. Three-channel MUAPs from six different MUs, detected from the right trapezius muscle during a 20-second computer work task (courtesy of M. Forsman, National Institute for Working Life, Göteborg, Sweden).

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 thus represent MUAPs for each respective MU detected at that particular recording point.

The first step in the decomposition is the segmentation of EMG data, i.e. extracting the active parts of the composite EMG signal and dividing 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 to all methods is finding 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.

After the segmentation step follows classification, i.e. sorting the segments into a number of groups (clusters) that each contains MUAPs from a specific MU. Every segment in a group shall be more similar to other segments in the same group than to a segment 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, i.e. MUAP 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 sustained contractions. Templates calculated by a complete-linkage technique may thus be influenced too greatly by their historical shapes, which could impair the classification. A golden mean between these two techniques may therefore be preferable in many cases.

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, RMS of the residual value between segment and template, and wavelet and power spectrum parameters describing the waveforms can be used for this purpose. In addition to these comparisons, minimum time inter-distance is often set to allow clustering between two firings. This is based on the fact that the motor axon innervating an MU, and its muscle fibres, should not physically be able to fire faster than a certain limit (see Chapter 1.2.2).

1.6 Muscle activity patterns – previous results

A number of studies have reported muscle activity patterns during low-level workloads, mainly for short-term contractions. This chapter briefly summarises some of these results.

1.6.1 Continuous motor unit activity

The validity of the Cinderella hypothesis in the context of computer work rests on 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. Studies have shown that the same 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 ten-minute attention-demanding computer work task, six of 38 recordings showed one or more trapezius MUs to be active throughout the whole work task (Waersted et al. 1996). In another study of ten-minute low-level trapezius 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). The latter phenomenon is called MU substitution and is further described in Chapter 1.6.4. A recent study of prolonged computer mouse work showed that some trapezius MUs may stay active at least as long as during the full session length (30 minutes), while others were intermittently active during the work task (Zennaro et al. 2003).

How long are these MUs able to stay active? For the EDC muscle, it has been reported that a subject has been able to deliberately keep one MU active for up to three hours and 17 minutes (Stålberg 1966). That study used single fibre biofeedback, not present in a normal working environment, to facilitate stable MU activity. Thus it is not obvious that Stålberg's results are valid in the context of a normal work task. Olsen et al. (2001b) studied the impact of fatigue on MU activity during a sustained low force contraction until exhaustion in the right extensor carpi radialis 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 SEMG signals, and decreased mean power frequency (MPF). Similar results have been found during submaximal fatiguing contractions of the vastus lateralis muscle, reporting a monotonic decrease in the recruitment threshold of all MUs without a change of the recruitment order (Adam and De Luca 2003). 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. A study of MU activity in a jaw muscle during induced experimental pain, by injection of capsaicin, reported a decreased MU firing frequency but without changes in the MU recruitment order (Sohn et al. 2000). Increased MU twitch force has been suggested as a compensatory mechanism for this discharge modulation (Sohn et al. 2004). 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 precision.

1.6.2 Motor unit doublets

During prolonged stereotype activity, occurrences of double discharges (MU doublets) of already exhausted MU fibres have been hypothesised as a potential additional risk for MU overuse (Søgaard et al. 2001). In the EDC muscle, MU doublets have been reported to be more frequent during double mouse click tasks than during slow finger-lifting tasks (Søgaard et al. 2001) or during slow ramp contractions (Sjøgaard et al. 2001). On the basis of these findings, recommendation has been made to avoid double clicks using the computer mouse (Kadefors and Läubli 2002). Doublets have also been found in the right upper trapezius muscle during double clicking with the right (Blangsted et al. 2001; Olsen et al. 2001a) and with the left (Olsen et al. 2001a) index finger. Previous to this thesis, comparative studies of MU doublet occurrences during double click versus other mouse click tasks have been lacking. Thus no previous data are available to make conclusions as to whether double clicks during computer work generally constitute a higher risk for WMSDs than do single clicks.

1.6.3 Low muscle rest – a risk factor for disorders?

On the basis of the Cinderella hypothesis, it has been postulated that a low degree of overall muscle rest entails a higher risk for development of WMSDs. This hypothesis is supported by a one-year prospective study in light manual industrial workers (Veiersted et al. 1993), where regression analysis showed that a low rate of short muscle rest periods (gaps) significantly predicted future development of WMSDs. Moreover, an extensive prospective study of computer users showed a significant association of perceived muscular tension with an increased risk for developing neck pain (Wahlström et al. 2004). Significantly higher median trapezius SEMG activity and tendency towards lower muscle rest were shown in subjects with perceived muscular tension (Wahlström et al. 2003). Veiersted et al. (1993) showed that the number of short muscle rest periods was significantly lower in the patients, also before patient status. Madeleine et al. (2003) carried out a prospective study of 12 newly employed healthy female workers in poultry and fish industries. After six months of employment, 50% of the workers had developed neck/shoulder pain and/or tenderness. Higher shoulder muscle SEMG activity was observed in workers who developed neck/shoulder complaints compared with workers who stayed healthy, for both zero and six months of employment recordings.

The two latter studies indicate that a low degree of muscle rest is at risk of being maintained even after the development of WMSDs. Cross-sectional field studies in medical secretaries (Hägg and Åström 1997) and cashier workers (Sandsjö et al. 2000) performing ordinary work activities, have reported significantly lower muscle rest among workers with self-reported neck/shoulder complaints compared to those without. However, similar studies in office workers (Nordander et al. 2000; Vasseljen and Westgaard 1995) did not support but rather contradicted these results. Thus, previous cross-sectional results are not fully consistent. Since these studies were mainly performed in daily life situations, this inconsistency might be related to differences between subjects in work tasks, ergonomic environment etc. Comparative studies of muscle rest during standardised computer work tasks in a controlled environment are therefore of high interest. Such studies comparing cases vs. non-cases are currently lacking.

1.6.4 Motor unit substitution and muscle compartmentisation

As opposed to the Cinderella hypothesis, other mechanisms may exist that overrule the size-order principle and "allow" MUs to be intermittently active. As previously mentioned, MU substitution has been reported by Westgaard and De Luca (1999) for the upper trapezius muscle. This behaviour has also been seen for the biceps brachii muscle during a prolonged, isometric elbow flexion of 10% of MVC (Fallentin et al. 1993). It has been shown for the rectus femoris muscle that the size-order principle was valid under conditions of a fixed posture and stable movements, while unstable recruitment orders and MU substitutions occurred in the case of free postures or changing movements (Person 1974). The underlying mechanisms of MU substitution remain unclear. Short gaps in muscle activity seem to promote the substitution process (Westgaard and De Luca 1999; Westgaard and Westad 2003), which is interesting considering the above-mentioned findings of significantly fewer gaps among subjects who develop WMSDs (Veiersted et al. 1993). It has also been found that brief pulses of higher contraction amplitudes may serve as a trigger to induce MU de-recruitment for MUs with initial threshold levels close to the working contraction level and recruitment of MU of higher thresholds (Westad and Westgaard 2001; Westad et al. 2003). Following the amplitude pulses, there was also a short marked reduction, lasting four seconds on average, in the firing rate of the still active MUs. These findings are supported by reported reductions of isometric shoulder elevation fatigue by periods of increased load (Mathiassen and Turpin-Legendre 1998). The control strategies also seem to differ between muscle groups. For example, low-threshold MUs in the trapezius muscle showed different control features in slow and fast contractions, while this was not seen in the non-postural first dorsal interosseous muscle (Westgaard and De Luca 2001; Westgaard and Westad 2003). In slow contractions (of the trapezius muscle), it was also found that recruitment of new MUs decreased the firing rate of already active MUs.

There may also be “substitution” mechanisms between larger pools of MUs also on a macro level, suggesting functional subdivision of the muscle in different compartments. McLean and Goudy (2004) reported findings of negative correlations in EMG RMS levels between three different recording sites inside the medial gastrocnemius muscle during sustained low-level activation. For the upper trapezius muscle, several SEMG studies have reported indications of functional subdivisions during prolonged, low-level contractions (Mathiassen and Winkel 1990; Mathiassen and Aminoff 1997; Mathiassen and Hägg 1997; Jensen and Westgaard 1997), with significantly different strategies between individuals (Mathiassen and Aminoff 1997). It has also been shown that the muscle activity can be voluntarily redistributed among synergists to the trapezius muscle (Palmerud et al. 1995, 1998). Alternating activity between synergistic muscles has also been reported during prolonged low-level knee extensions (Sjøgaard et al. 1986; Kouzaki et al. 2004) and ankle flexion/extensions (Tamaki et al. 1998). This suggested non-constant activation of motor pools - within a muscle or between synergists - is not equivalent to MU substitution; it is nevertheless interesting from a physiologically/ergonomically point of view considering short-term and long-term effects for e.g. muscle fatigue and pain development. For example, van Dieën et al. (1993) showed that subject groups with a high endurance capacity in repetitive high-level trunk extensions demonstrated significantly more alternations of SEMG activity between different parts of the erector spinae muscle than those with lower endurance capacities.

1.7 Aims of this thesis

The main scope of this thesis was to investigate whether muscular activity patterns during tasks simulating computer work are consistent with the Cinderella hypothesis on selective MU overuse. Specifically, the aims were:

A: To investigate the existence of continuous and sustained MU activity in pain-free subjects during:

- a static, prolonged, low-level workload (trapezius and EDC muscles)
- wrist movements (EDC muscle)
- a prolonged standardised computer work task (trapezius muscle)

Hypothesis: continuously active MUs are prevalent during all these tasks and in both muscles investigated. This would support the Cinderella hypothesis on continuous and sustained MU activity in the context of computer work.

B: To investigate the existence of and disposition for MU doublets (EDC muscle), and the overall muscle activity levels (trapezius, EDC and flexor carpi ulnaris, FCU, muscles), in pain-free subjects during single versus double mouse clicks in a prolonged simulated computer work task.

Hypothesis: MU doublets are more prevalent in double clicks. This would imply that double clicks should be avoided when carrying out a computer mouse work task.

C: To investigate the degree of muscle rest in subjects with versus without neck/shoulder complaints during different short-term (two to five-minute) standardised computer work tasks.

Hypothesis: subjects with neck/shoulder complaints show less muscle rest compared to those without complaints. This would support the Cinderella hypothesis in the context of an activity-based pathogenesis and maintenance of myalgia.

2 Methods and materials

This chapter presents the methods and materials used in Papers I-V (see summary in Table 1). Specific protocols and subject data for each study are further presented in Chapter 3.

The Research Ethics Committee of Gothenburg University approved the studies reported in Papers I-IV. The study reported in Paper V was approved by the local research ethics committees for each site (Gothenburg and Copenhagen).

Table 1. Summary of methods used in Papers I-V.

	Paper				
	I	II	III	IV	V
Number of subjects	8	8	4	11	79
Work task(s)	Prolonged static contraction	Prolonged static contraction / wrist motions	Prolonged computer editing	Prolonged computer editing	Typing, editing, stress & precision computer tasks
Task length	60 min	25 min / 20 s	60 min	60 min	5 min*
Surface/intramuscular EMG (Y/N)	Y/Y	Y/Y	Y/Y	Y/Y**	Y/N
SEMG technique	1-ch bipolar, 20-mm IED	1-ch bipolar, 20-mm IED	1-ch bipolar, 20-mm IED	1-ch bipolar, 20-mm IED	7-ch bipolar, 5-mm IED***
Muscles studied	Right trapezius	Right EDC	Right trapezius	Left & right trap., right EDC & FCU	Left & right trapezius
Additional measurements		Goniometry		Mouse force	NMQ questionnaire

* Except for the precision task, which lasted for 2 minutes

** Intramuscular EMG from the EDC muscle, analysed in 3 subjects

*** Converted to 1-channel bipolar SEMG with 20-mm inter-electrode distance (IED)

2.1 Subjects

In the studies reported in Papers I-IV, none of the subjects had experienced any pain or discomfort in the neck/shoulder region or the upper extremities during the last month, and all were right-handed. Both females and males were included. In Paper V, elderly female computer users (defined as 45-65 years), with and without self-reported neck/shoulder complaints, participated. All subjects were informed in full about the experimental procedures before giving their consent, and were fully allowed to interrupt their participation at will.

2.2 Electromyography

SEMG techniques were chosen to obtain a measure of overall activity levels in the muscles studied, and intramuscular EMG was chosen to detect MU activity patterns (Papers I-IV).

In the studies described in Papers I-IV, bipolar SEMG was measured by two silver/silver-chloride electrodes (N-00-S Blue Sensor, Medicotest, Denmark)

(Figure 7A) with an inter-electrode distance (IED) of 20 mm, according to the general recommendation of the SENIAM project (Freriks et al. 1999). Muscles studied were the upper trapezius muscle (Papers I and III-IV), the right EDC muscle (Papers II and IV) and the right FCU muscle (Paper IV). For the upper trapezius, the electrodes were placed 20 mm medially from the midpoint of the line between the dorsal processus of the seventh cervical vertebra and the acromion. This position – instead of 20 mm lateral to the midpoint as recommended by e.g. Mathiassen et al. (1995) – was chosen in order to ensure the necessary muscle thickness for insertion of intramuscular EMG electrodes. For the right EDC and FCU muscles, the electrodes were placed at approximately one-third of the distance from the lateral epicondyle to the lateral styloid processus. According to the recommendation of Zipp (1982), the final positions were confirmed by palpation while the index finger was moved. One ground electrode was placed on the skin on the dorsal processus of the seventh cervical vertebra (Papers I, III and IV) and on the lateral styloid processus (Paper II).

In Paper V, SEMG was measured from the upper trapezius muscles by a seven-channel bipolar linear silver/silver-chloride array electrode with 5 mm IED (ELSCH008, LISiN-SPES Medica, Italy; Pozzo et al. 2004) (Figure 7B). The electrodes were aligned parallel to the line between the dorsal processus of the seventh cervical vertebra and the acromion. Before array placement, the skin was slightly abraded with abrasive paste. Conductive gel was injected into each electrode cavity by means of a gel dispenser. A reference electrode was placed at the wrist. This study was undertaken within the EU project ‘Neuromuscular Assessment of the Elderly Worker (NEW)’ (Merletti et al. 2004). One of the objectives within the NEW project (outside the scope of the study in Paper V) was to investigate the non-invasive possibilities for estimating muscle fibre conduction velocity among elderly computer users, hence the use of a bipolar linear array electrode with an IED of less than 20 mm.

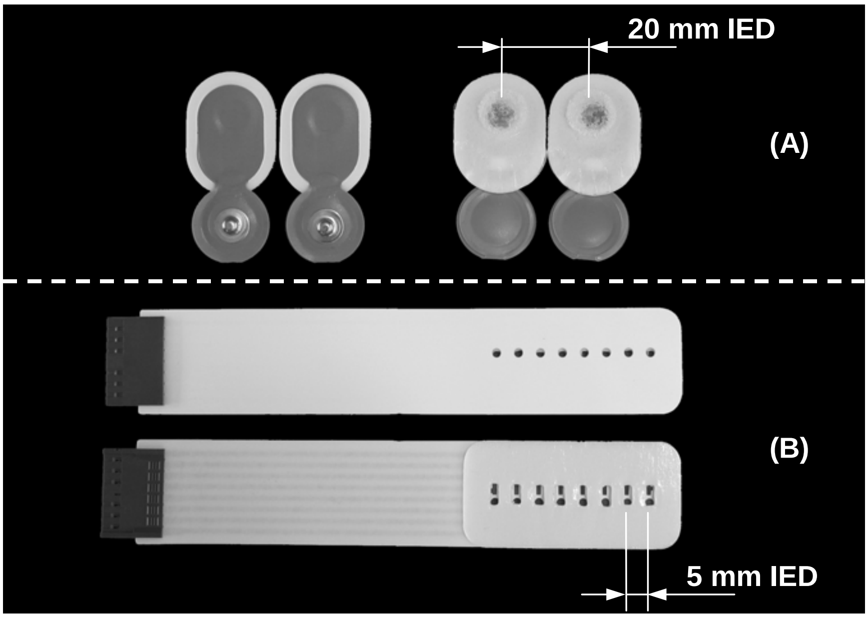

Figure 7. The Blue Sensor pre-gelled electrode pairs (A) used in the studies reported in Papers I-IV, and the NEW prototype multi-electrode linear array (B) used in Paper V. The holes for injection of conductive gel are visible on the upper electrode in Figure 7B. The lower electrode shows the 8 electrode cavities, surrounded by adhesive padding.

For the intramuscular EMG (Papers I-IV), a quadrifilar wire electrode was made using four 0.07-mm, Teflon®-insulated stainless medical steel wires (791000, A-M Systems Inc., USA), de-insulated 0.3 mm at the tip, twisted together and inserted in a 0.9-mm hypodermic needle (Figure 8). 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, prior to the attachment of surface electrodes, inserted into the right trapezius muscle (Papers I and III) and into the right EDC muscle (Papers II and IV) at the same points as previously described for the surface electrodes. 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, and three channels of bipolar intramuscular EMG could be recorded.

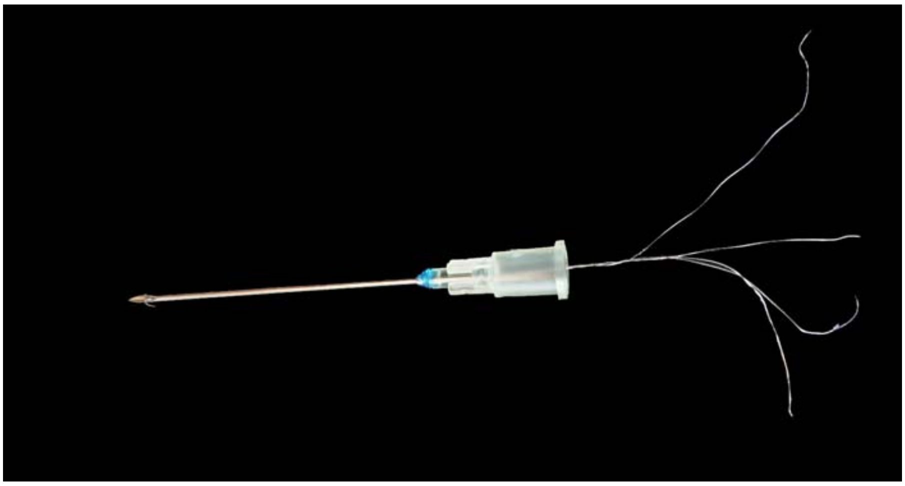

Figure 8. The intramuscular EMG wires, inserted in the hypodermic needle.

In Papers I-IV, both surface and intramuscular EMG signals were, after an 8 kHz low-pass filtering, simultaneously recorded on a computer hard disk with a 20 kHz sample frequency. In Paper V, SEMG was 16-bit A/D converted and 2048 Hz sampled on a prototype portable acquisition system (EMGlogger, LISiN – Sirio Automazione, Torino, Italy; Pozzo et al. 2004).

2.3 Goniometry

In the study reported in Paper II, a bi-axial electrogoniometer (Penny and Giles Biometrics, Blackwood, Gwent, UK) was used for measuring the wrist flexion/extension and ulnar/radial deviation. The goniometer was affixed on the dorsal side of the hand and forearm. The flexion reference angle was measured with the palm of the hand and the forearm pronated and resting on a table surface. The deviation reference angle was defined as the angle with hand and arm hanging relaxed along the body. The goniometer data was recorded simultaneously with the surface and intramuscular EMG data on a computer hard disk with a 20 kHz sample frequency.

2.4 Mouse force

The study reported in Paper IV used a left mouse button force-sensitive Intellimouse (Johnson et al. 2000) (Figure 9). This instrumented mouse facilitated identification of occasions of single and double mouse clicks. The left mouse button force was recorded simultaneously with the surface and intramuscular EMG data on a computer hard disk with a 20 kHz sample frequency.

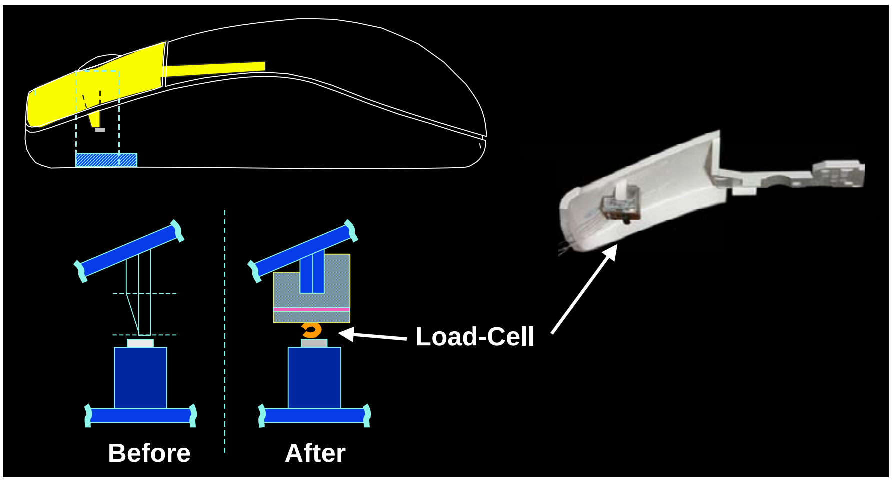

Figure 9. The force-sensitive computer mouse (courtesy of PW. Johnson, Univ. of Washington).

2.5 Questionnaires

In Paper V, a division into neck/shoulder cases and non-cases was made using self-reported data from the Standardised Nordic Musculoskeletal Questionnaire (NMQ) (Kourinka et al. 1987). The inclusion criterion for cases/non-cases was >30/<8 days of complaints in the neck and shoulder area during the last year. Here, both cases and non-cases should report less than three additional body regions with complaints >30 days. The subjects were also required to: (1) have worked at least five years with the present tasks, (2) work at least 20 hours a week and (3) have less than three months out of work, except for vacation, during the last five years.

2.6 Signal processing

Prior to analysis, the goniometer and mouse force data (Paper IV) were 10 Hz low-pass filtered, the SEMG data were 20-500 Hz (Papers I-IV) or 20-300 Hz (Paper V) band-pass filtered, and the intramuscular EMG data were 450-4500 Hz band-pass filtered, all with sixth-order, no-delay[6] filters. In Paper V, an adaptive 50 Hz rejection filter (Mortara, 1977) was also applied to the signals.

2.6.1 Overall muscle activity

SEMG RMS was calculated with window lengths of 200 ms (Papers I-III) and 100 ms (Papers IV-V), respectively. The formula for $SEMG_{rms}$ is:

$$SEMG_{rms}(i) = \sqrt{\frac{\sum_{k=1+(i-1)*N}^{i*N} SEMG(k)^2}{N^2}} \qquad i = 1, 2, \ldots \frac{N_{tot}}{N}$$

---

[6] Third-order Butterworth, executed with the "filtfilt" command in MATLAB

where N is the number of samples within each RMS window and N_{tot} the total number of samples acquired. The SEMG RMS levels were normalised to the electrical activity during MVCs, according to the recommendations of Mathiassen et al. (1995). The subjects performed the trapezius MVCs by pressing the elbows upwards against a constraining surface, while both elbows were flexed 90° and shoulders abducted 90° in the frontal plane, seated in an upright position. The MVCs for the EDC and the FCU muscles were performed with the fingers pressing upwards (EDC) and downwards (FCU), respectively, against a constraining surface, with the right shoulder abducted 25°, the elbow flexed 60°, and the lower arm and hand resting on a table.

In Paper V, the 7-channel 5-mm IED bipolar configuration (Figure 7B) was, prior to RMS calculation, converted to a 4-channel 20-mm IED configuration as:

$$s20_i = \sum_{k=0}^{3} s5_{i+k} \qquad i = 1, 2, 3, 4$$

where $s20_i$ was the i^{th} 20-mm IED signal and $s5_{i+k}$ the $(i+k)^{th}$ 5-mm IED signal. From visual inspection, the signal with best quality of these four was chosen for RMS calculation. The complete file was disregarded in the case that there were no usable combinations of four consecutive 5-mm IED signals available.

Muscle RRTs and gap frequencies were calculated with 1 %MVE as the threshold level for muscle rest.

2.6.2 Motor unit activity

A semi-automatic in-house program was used for the decomposition and classification of intramuscular EMG data into MUAPs (Papers I, II and IV). The program was an improved version of a previously used program (Forsman et al. 1999, 2001) (Figures 5 and 6), based on MATLAB (MathWorks Inc., USA). 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 prolonged 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 an MUAP and a template was calculated as:

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 thus far. Any 20-second period could, after the automatic phase, be decomposed more accurately 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, is 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 with the MUAP shape. An in-house 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 cluster automatically.

Classification rate was defined as the percentage of segments that could be classified into a specific MU. In Papers I-III, the criterion used for continuous firing was at least one identified firing in a two-second moving window. In Paper IV, MU double discharges with inter-firing intervals less than 20 ms were identified as MU doublets.

2.7 Statistics

Statistical analysis was done in MATLAB (Papers IV-V) and SPSS (SPSS Inc., USA) (Paper V). For normally distributed data, descriptive statistics was given by mean, range, standard deviation (SD) and/or coefficient of variation[7] (CV), and possible differences between different groups were tested by paired and non-paired t-tests. For non-normally distributed data, non-parametric statistics (Wilcoxon and Mann-Whitney tests) was applied. In Paper IV, the total number of observed doublets during single versus double clicks was compared by the Fisher exact probability test for independent samples. In Paper V, the correlation between RRT values and p10 SEMG RMS levels was investigated by the Spearman correlation test. The chosen level of significance was $P<0.05$. $P<0.1$ was chosen as the limit to indicate tendency of differences.

---

[7] CV = SD/mean

3 Summary of papers

3.1 Paper I

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

3.1.1 Subjects

Eight subjects, four males and four females, participated in the study. Their mean age was 40 (range: 29-53) years, mean weight 71 (52-109) kg, and mean height 173 (155-190) cm.

3.1.2 Protocol

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 trapezius 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.

3.1.3 Results

The mean SEMG RMS level was 5.0 %MVE (range: 4.2-6.1 %MVE), while the mean CV was 23% (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 MPF did not decrease significantly during the experiment. Altogether in the eight subjects, 108 different MUs (range: 10-19) were identified and tracked. The mean classification rate was 86% (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 for the three subjects, respectively.

3.1.4 Conclusion

Some motor units were continuously active while others were intermittently active during a one-hour low-level static work task. The results lend support to the Cinderella hypothesis on selective overuse of low-threshold trapezius MUs in the context of prolonged static muscle activations, characteristic for computer work.

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.

3.2.1 Subjects

Eight subjects, six males and two females, participated in the study. Their mean age was 37 (range: 27-52) years, mean weight 76 (52-109) kg, and mean height 178 (154-190) cm.

3.2.2 Protocol

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 static isometric low-level contraction and then 20-second periods of maximal voluntary wrist flexion/extension and ulnar/radial deviation movements. For purposes of normalisation, the subject performed maximal voluntary contractions in the direction of the wrist extension at the end of the experiment.

3.2.3 Results

The SEMG RMS in one of the subjects showed great fluctuation, with a CV of 35%, and the subject was therefore excluded from further analyses. The mean CV of the SEMG (25 minutes of 0.2-second RMS values) in the other subjects was 17%. 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 one subject, 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.

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. For the ulnar/radial deviation recordings, MUs were identified from all eight subjects. The signals of the flexion/extensions were more difficult to decompose because of the 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 ten firings per second throughout the range of motion were observed in nine of the 16 trials. MUs with more than ten firings per second throughout the range of flexion/extension motion were observed in all six trials that could be analysed.

3.2.4 Conclusion

Some MUs in the EDC were continuously active for at least 25 minutes of low-level static contraction, while others were intermittently active. Furthermore, there were MUs that were active in all phases of full range of motion of wrist movements. The results support the Cinderella hypothesis on selective overuse of EDC muscle MUs in the context of prolonged static muscle activations and wrist motions, characteristic for computer work. Further investigations are needed for work tasks more closely resembling computer work.

3.3 Paper III

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

3.3.1 Subjects

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

3.3.2 Protocol

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 90° angle between the upper and lower arm if so desired by the subject. The positions of the mouse, keyboard and computer screen were chosen by the subjects according to their preferences. 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. There was no time pressure or demand for perfection.

3.3.3 Results

Subject 4 was excluded owing to poor quality of the intramuscular EMG signals. The median SEMG levels for subjects 1-3 were 7.1, 14.1 and 3.3 %MVE, respectively. It was observed in video recordings that subjects 1 and 2 lifted their shoulders during the keyboard input task, which may have induced periodical SEMG increases, as compared to subject 3. The mean classification rate of decomposed intramuscular EMG segments into one or several MUAPs was 87% in 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 ten of 15 MUs identified fired 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 sustained 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.

Moreover, there was a tendency for subjects who showed continuous MU activity in the trapezius muscle during prolonged static work (Paper I) to also show this in the EDC muscle (Paper II) and in the trapezius muscle during computer work (Paper III). (A previously unpublished finding).

3.3.4 Conclusion

The study showed an existence of continuously and sustained MU activity in a computer work task. The results support the Cinderella hypothesis on selective overuse of low-threshold trapezius MUs in the context of computer work. Intermittently active MUs were also found. The reasons for the intra- and inter-individual differences remain unstudied.

3.4 Paper IV

The aim of this study was to compare muscle activity levels of single and double mouse clicks during a prolonged combined mouse/keyboard work task, with special reference to the concept of MU doublet firings.

3.4.1 Subjects

Eleven right-handed subjects (seven males and four females) volunteered to participate in the study. They were all experienced computer users without any reported upper limb complaints during the previous month. Mean age was 30 (range: 21-47) years, mean weight 70 (62-85) kg, mean height 175 (162-192) cm.

3.4.2 Protocol

SEMG were studied from left and right upper trapezius, right EDC and right FCU. Moreover, MU activity in the EDC muscle was analysed through intramuscular EMG during 50 consecutive mouse clicks in three of the subjects. The subjects performed the same work task as described in Paper III. For each mouse click, a median and a 90th percentile (p90) value was obtained within a 0.5-second window, approximately centred at the click actuation, and the values during single versus double clicks were compared.

3.4.3 Results

Average SEMG RMS levels for the complete work task were 4.0, 6.2, 11.7 and 2.2 %MVE for the left/right trapezius, EDC and FCU muscles, respectively. Median and p90 RMS levels during single vs. double mouse clicks are shown in Table 2.

Table 2. Median and p90 RMS levels for muscles studied during the single and double mouse clicks, respectively. * indicates significant difference between single and double clicks, # indicates a tendency toward a corresponding difference (P<0.1).

		Left trapezius	**Right trapezius**	**EDC**	**FCU**
Median RMS	Single clicks	4.1*	3.4*	9.2	1.4
	Double clicks	3.1	2.7	12.1	1.9
p90 RMS	Single clicks	5.7*	7.6*	20.1#	3.7
	Double clicks	4.5	4.1	17.6	3.6

The median levels differed significantly between single and double clicks for the left and right trapezius muscles but not for the EDC and FCU muscles. The differences in p90 levels between single and double clicks were significant in the left and right trapezius muscles, tended to be different in the EDC muscle, and were not significant in the FCU muscle. In the three subjects with MU activity analysed, the total number of doublets identified during single/double clicks were 19/16, 5/0 and 0/0, respectively. None of the differences were significant.

3.4.4 Conclusion

The results indicate that double clicking produces neither higher median nor p90 levels in the trapezius and EDC muscles, nor a higher disposition to MU doublets, than does single clicking. The indications were rather the opposite, especially for the p90 levels. Although it cannot be concluded from the present study that double clicks are harmless, there were no signs that double clicks during computer work generally constitute a larger risk for WMSDs than do single clicks.

3.5 Paper V

The objective of the study was to investigate whether computer users with self-reported neck/shoulder complaints (cases) show less RRT than non-cases when performing standardised, short-term computer work tasks.

3.5.1 Subjects

Elderly female computer users from Denmark and Sweden participated in the study. For subject screening, see Sandsjö et al. (2005) and Sjøgaard et al. (2005). As described in Chapter 2.5, division into neck/shoulder cases and non-cases was made by data from the NMQ Questionnaire (Kourinka et al. 1987). In total, 79 subjects (35 cases, 44 non-cases) were studied, with a mean age of 53.3 (SD: 5.0) years in cases and 55.6 (4.9) years in non-cases and a mean body mass index (BMI) of 25.7 (3.9) in cases and 24.6 (3.1) kg/m^2 in non-cases. For each work task, an average of 15 (range: 14-16) of the cases and 18 (12-21) of the non-cases showed, by visual inspection, analysable SEMG files. Here, average age and BMI were similar to those representing all 79 subjects, and no differences in age or BMI between cases vs. non-cases were found for any of the work tasks.

3.5.2 Protocol

The subjects performed four work tasks, (1a, 1b, 2 and 3), 1-3 in random order:

1. Typing (1a) of a standard text, followed by editing (1b) of the typed text according to a standard procedure (Juul-Kristensen et al. 2004). Each task lasted until completion or five minutes.
2. A stress task (Stroop 1935; Laursen et al. 2002) for five minutes.
3. A precision mouse work task (Birch et al. 2000c) for two minutes.

SEMG was measured in the upper trapezius muscle on the side operating the computer mouse (mouse side) and on the side not operating the mouse (non-mouse side). After normalisation to MVE, the cases' and non-cases' median and p10 SEMG RMS levels and RRT values were calculated and compared.

3.5.3 Results

The median SEMG activity levels during the typing, editing, precision and stress tasks were 9.7, 8.5, 2.1 and 1.8 %MVE on the mouse side and 8.1, 6.6, 1.2 and 1.9 %MVE on the non-mouse side. Significantly lower RRTs were found for cases for the stress task on the mouse side. Here, there was also a tendency toward higher median RMS levels in cases vs. non-cases. Also the p10 RMS levels were on average higher in cases with a relatively low P-value ($P<0.13$). On the non-mouse side, there was a tendency toward higher p10 RMS levels and lower RRT values for cases vs. non-cases. No differences between cases and non-cases were found in the typing, editing and precision tasks. The p10 RMS levels correlated significantly and inversely with the RRT values on both the mouse and non-mouse sides for all tasks (Spearman test; ρ_s ranging between -0.81 and -0.95).

3.5.4 Conclusion

For the stress task, the results showed several electromyographic signs for less trapezius muscle rest among cases compared to non-cases. No such signs could be found for the typing, editing and precision mouse work. The present results indicate an increased motor response to psychological stress among subjects with self-reported neck/shoulder complaints.

4 Discussion

In this thesis of muscular activity patterns in standardised light manual work tasks, the main findings were:

- Continuous and sustained MU activity was found in both the trapezius and the EDC muscles during prolonged work tasks (60 and 25 minutes for the trapezius and EDC muscle studies, respectively), characterising computer work.
- MU doublets were found during both single and double mouse clicks. The SEMG results did not imply that the risk for generation of doublets was higher for double clicks than for single clicks, rather the reverse.
- Subjects with self-reported neck/shoulder complaints tended to show less muscle rest, compared to those without complaints, when performing a short-term standardised stress task. No differences were shown for other work tasks performed (typing, editing and mouse precision work).

Continuous and sustained MU activity has not previously been investigated in the EDC muscle, and, in the trapezius muscle, only for task lengths up to ten and (recently) 30 minutes. Thus, the present findings of continuous and sustained MU activity for 60 minutes in the trapezius muscle and for 25 minutes in the EDC muscle are both novel. Also the comparative findings of MU doublets during single and double mouse clicks are novel; analyses of MU doublets during both single and double clicks – and of SEMG levels during the click actuations – have not been undertaken before. Finally, previous studies of muscle rest differences between subjects with and without neck/shoulder complaints have mainly been carried out at the subject's ordinary workplace during regular work. With respect to the results, important factors such as work tasks, psychosocial and ergonomic environment etc., can differ between individuals, subject groups and days. The novelty of the present findings is that differences in muscle rest between subjects with and without complaints can also be detected for a standardised computer work stress task in a controlled laboratory setting.

4.1 Continuous vs. intermittent motor unit activity

The results reported in Papers I-III show that there is a possibility for MUs to be continuously active during prolonged work tasks, such as in computer work, in both the trapezius muscle and in the EDC finger/wrist extensor muscle. Furthermore, EDC MUs were active in all phases of full range of motion of wrist movements. These results lend support to the Cinderella hypothesis (Hägg 1991) – and the hypothesis by Hagberg (1981, 1982, 1984) – on a selective overuse of specific MUs in the context of computer work. Eventual changes over time of recruitment thresholds were not investigated for the MUs detected. It can thus not be confirmed whether the Cinderella "first in – last out" principle was prevalent for the MUs found with continuous and sustained activity. Continuous MU activity has previously been reported in the trapezius muscle during ten minutes of low-level muscle work (Waersted et al. 1996; Westgaard and De Luca 1999) and recently also during 30 minutes of computer mouse work (Zennaro et al. 2003). To the author's knowledge, one hour of continuous trapezius MU activity has not previously been reported. The continuous and sustained EDC

MU activity during voluntary contraction is also novel, although a previous experiment in the biceps brachii, EDC and frontal muscles reports that subjects were able to, with visual feedback of the intramuscular signal, deliberately keep a single MU active for up to three hours and 17 minutes (Stålberg 1966).

The present results also indicate that many MUs do not necessarily follow a continuous and sustained activity pattern. Instead, some MUs seem to show on/off behaviour, presumably owing to MU substitution (de-recruitment of one MU followed by recruitment of another). These findings are consistent with those of Waersted et al. (1996), Zennaro et al. (2003) and Westgaard and De Luca (1999), with the exception that the latter study reported a more synchronised on/off pattern in many of the non-continuously active MUs. Similar MU patterns were reported in the biceps brachii muscle by Fallentin et al. (1993). The underlying mechanisms of MU substitution have been investigated by e.g. Westad and co-authors (2001, 2003), but remain a research question.

Apart from these intra-individual differences in MU activity patterns, the results of this thesis also indicate inter-individual differences; some subjects showed a higher amount of continuous and sustained MU activity than did others. This was also reported in a study of prolonged computer work by Zennaro et al. (2003). Two possible explanations may be: (1) different MU recruitment strategies between different human beings and (2) different work strategies. An earlier study showed that a subject could, by SEMG data feedback, perform the same work task at different trapezius muscle load levels (Palmerud et al. 1995). A third possible explanation for the inter-individual differences shown has to do with the methods used. To make it possible to record EMG pulses originating from single MUs, the intramuscular recording volume must be restricted to detect only a few MUs (see also Chapter 1.4.1). The active muscle, on the other hand, consists of hundreds of MUs or more. At present, it is unclear to what extent the activity patterns in detected MUs can be generalised to a larger part of the muscle studied. Differences in MU activity patterns between repeated measurements, for instance, might very well be as large as between subjects. Nevertheless, it is interesting to note that there was a tendency for subjects who showed continuous MU activity in the trapezius muscle during prolonged static work (Paper I) to also show this in the EDC muscle (Paper II) and in the trapezius muscle during computer work (Paper III).

4.2 Motor unit doublets

Previous research has investigated various situations in which MU doublets tend to be more frequent. In addition to being an effect of different neuromuscular diseases (Partanen and Lang 1978) and muscle fatigue (Griffin et al. 1998), doublets have been reported in various muscles: (1) during static contractions at the borderline of an MU threshold level (Garland and Griffin 1999), (2) at the onset (Desmedt and Godaux 1977; Bawa and Calancie 1983) as well as later in the EMG burst (van Cutsem et al. 1998) of fast, or ballistic, contractions, and (3) at the recruitment and de-recruitment of an MU (Denslow 1948; Bawa and Calancie 1983; Kudina and Alexeeva 1992).

The significantly higher p90 values for single clicks in the left and right trapezius muscles and the tendencies toward higher p90 values during single clicks in the right EDC muscle, as reported in Paper IV, imply a wider range of muscle activity during single clicks in these muscles. A larger number of MUs would therefore be expected to be recruited and de-recruited during single vs. double clicks. Thus, the SEMG results in Paper IV do not imply a higher disposition to MU doublets during double clicking than single clicking a computer mouse. The indications are rather the opposite, and agree with the intramuscular analysis in a selection of the subjects showing a slightly higher number of identified MU doublets in the EDC muscle during single vs. double clicks. It should be noted, however, that the intramuscular results presented in Paper IV originate from a limited amount of data (three subjects and a total of 150 analysed mouse clicks), and that the differences between single vs. double clicks were not significant.

A frequent occurrence of MU doublets has previously been reported in the EDC muscle during double clicking a computer mouse but not during slow finger-lifting tasks (Søgaard et al. 2001) or slow ramp contractions (Sjøgaard et al. 2001). Doublets have also been found in the right upper trapezius muscle during double clicking with the right (Blangsted et al. 2001; Olsen et al. 2001a) and with the left (Olsen et al. 2001a) index finger. Analyses of MU doublets during both single and double mouse clicks have not previously been reported.

As one of the results of a recently completed EU project (PROCID), a list of six recommendations for healthier computer work was suggested (Kadefors and Läubli 2002). These include e.g. that computer operators should limit repetitive finger movements and constrained postures, be allowed to take frequent breaks and mental relaxation periods, and should avoid double clicks using the computer mouse. The latter recommendation is based on the findings of MU doublets by Sjøgaard et al. (2001) and Søgaard et al. (2001). The present results do not suggest that double clicks during computer work would generally constitute a higher risk for WMSDs than do single clicks. It could also be discussed whether MU doublets during mouse work at all constitute a risk for WMSDs, compared to the static and continuous activity caused by lifting hand/fingers just above the mouse buttons. In the context of development and maintenance of WMSDs, the ability to have periods of muscle rest might be a more important issue.

4.3 Lack of muscle rest

The results of the stress task in Paper V lend support to the hypothesis that subjects with neck/shoulder complaints show less trapezius muscle rest than those without complaints, as previously suggested by e.g. Hägg and Åström (1997) and Sandsjö et al. (2000). It should be emphasised that two similar studies of office workers (Nordander et al. 2000; Vasseljen and Westgaard 1995) do not support but rather contradict these results.

During repeated maximal forward shoulder flexions, each followed by attempted total relaxation, female cleaners with trapezius myalgia were reported to show a significantly higher rest-to-max SEMG ratio than healthy female controls (Larsson et al. 2000a). In an extensive intramuscular study, mainly of the trapezius muscle, action potentials could be continuously recorded more often in typists with myalgia than in the healthy subjects when performing repetitive typewriting with one finger (Lundervold 1951). Although with test set-ups considerably different from that in Paper V, both studies may support the hypothesis of less ability for muscle rest among subjects with neck/shoulder complaints.

Results of some previous studies show a hampered ability for muscle rest among subjects with neck/shoulder complaints (cases) also after working hours. In a study of service workers with work stress and low biomechanical exposure, cases showed unchanged trapezius muscle activity between work and leisure while non-cases had significantly lower activity during leisure time (Holte and Westgaard 2002). Even during sleep, trapezius muscle activity has been shown to of be significantly higher level and of longer duration in cases than in non-cases (Mork and Westgaard 2004).

In the results of Paper V, indications of different RRT and SEMG levels between cases and non-cases could be found for the stress task but not for the typing, editing or mouse precision work tasks. The relatively intensive and static physical demands during the typing and editing tasks, and the shorter recording time during the mouse precision task, may possibly have masked eventual differences in muscle activities between cases and non-cases. An alternative explanation is that subjects with self-reported neck/shoulder complaints are more prone to develop stress-related trapezius muscle activity than healthy subjects, i.e. there is an increased motor response to psychological stress in tender muscles. In a study of 62 subjects with trapezius muscle myofascial trigger points, spontaneous needle EMG activity was reported from all trigger points but not from adjacent non-tender fibres of the same muscle in the same subject (Hubbard and Berkoff 1993). It was postulated that the trigger point activity was generated from sympathetically stimulated muscle spindles, which is further supported by findings of increased trigger point activity during psychological stress while adjacent non-tender trapezius muscle fibres remained electrically silent (McNulty et al. 1994).

As previously suggested by Veiersted et al. (1993), a lack of muscle rest periods entails a higher risk for development of WMSDs. Due to the cross-sectional design of the study in Paper V, it cannot be said whether the cases also showed less muscle rest than non-cases before the complaints developed. Veiersted et al. (1993) demonstrated that the number of short muscle rest periods was significantly lower for the patients also before patient status. Moreover, a prospective study of light manual workers in the poultry and fish industries has shown that workers who later developed neck/shoulder complaints showed higher shoulder muscle SEMG activity both prior to and after the start of complaints, compared with workers who stayed healthy (Madeleine et al. 2003). With the support of these longitudinal findings, the present findings of reduced muscle rest among cases suggest that stressful working conditions – especially in subjects with neck/shoulder complaints – increase the risk for muscular overuse.

4.4 Methodological considerations

4.4.1 Study designs and subjects

The scientific approach in all papers was quantitative and hypothesis testing. In the case of Papers I-III, no statistical tests were performed; the issue here was to investigate whether MUs with continuous and sustained activity existed at all during low-level workloads simulating computer work. For the same reason, the number of subjects studied was relatively small; eight in Papers I-II and four in Paper III. Paper IV was part of a larger intramuscular study. Thus there were a relatively limited number of subjects studied here. In part, this was compensated for by the large number of single and double mouse clicks studied per subject. Papers I-IV were all case studies. Paper V was a cross-sectional study. However, the subjects were not randomly screened (Sandsjö et al. 2005). Thus, they cannot be considered representative of their work place/organisation, occupation or the workforce in their respective countries.

In Paper I-IV, only healthy subjects – i.e. subjects without any self-reported neck/shoulder/forearm soreness and/or complaints during the last month – were investigated. The main objective here was to investigate the "normal" muscular activity during simulated computer work, i.e. among pain-free subjects. It has recently been reported that subjects with severe neck/shoulder complaints activated more MUs – and an increased duration of individual MU activity – than did subjects with moderate complaints, both performing a five-minute finger-tapping task (Zennaro et al. 2004). The study of Zennaro and co-workers is to the author's knowledge the only comparative study of MU activity duration vs. health differences thus far reported, at least in the context of computer work.

4.4.2 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 continuously active MUs exist at all in the trapezius and EDC muscles during simplified work tasks, chosen to be closely similar to computer work. The next step was to study MU firing patterns during a more realistic computer work task, as in Paper III.

In Papers III-IV, the subjects performed a prolonged computer work task that contained a common operation used in the context of a text editing process. In order to keep the task simple and comparable between subjects, a standardised work task was chosen. Previous studies have also detected continuously active MUs during other prolonged computer work tasks slightly different from the present one, e.g. for a ten-minute keyboarding task (Westgaard and De Luca 1999) and a 30-minute "click-and-drag" task using a computer mouse (Zennaro et al. 2003), supporting the data reported in Paper III.

The computer work tasks in Paper V were also standardised. Previous comparative studies of muscle rest time (e.g.: Blangsted et al. 2003; Hägg and Åström 1997; Nordander et al. 2000; Sandsjö et al. 2000; Vasseljen and Westgaard 1995) are mostly of a prolonged character and have been carried out at the subject's workplace during regular work. Field studies such as these facilitate estimations of the individual's actual workload during their working hours. However, there is a risk that a comparative analysis of workload between subject groups (e.g. cases vs. non-cases) can be hampered by factors difficult to control at the workplace. For example, work tasks, psychosocial factors, ergonomic environment etc. may differ between individuals, subject groups and days. A field study of personnel in municipal administration showed that differences in muscle rest predominantly were due to differences in job content, even though all performed computer work (Blangsted et al. 2003). Comparative studies in a controlled laboratory setting and with standardised work tasks, as in Paper V, are therefore of great interest.

The use of intramuscular measurements (Papers I-IV) 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. Therefore, the subjects were brought to a standardised environment that was new to them. This may cause the subject to perform the work task differently than he/she would otherwise do, and may also 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 MUs can be found to be active both under psychological and physical workloads (Forsman et al. 2000; Lundberg et al. 2002). In the future, it may be possible to introduce MU detection in field studies, using multi-array SEMG electrodes (e.g.: Disselhorst-Klug et al. 2000; Zwarts and Stegeman 2003).

As mentioned above, eventual changes in recruitment thresholds over time were not investigated for the MUs detected, wherefore it cannot be stated whether the Cinderella “first in – last out” principle was prevalent in the continuously active MUs found. A majority of the MUs detected were active at levels corresponding to 5-10 %MVE and below. It is consequently reasonable to assume that the MUs were primarily of a low-threshold character.

4.4.3 Electromyography – technical considerations

Intramuscular EMG was chosen for detecting MU activity patterns. Wire electrodes were selected, since they are suitable for studies of MU firing patterns during dynamic work tasks. 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.

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 MUs with continuous and sustained activity. This may affect the results in at least two important ways: (1) by underestimation of the number of subjects with continuously active MUs and (2) by limited method repeatability. The latter makes it difficult to use the present method for comparisons between individuals. 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.

Finally, SEMG is at present the most established and best-known technique for recording overall muscle activity and was therefore chosen for that purpose. Using pre-gelled adhesive surface electrodes with 20 mm IED (as in Papers I-IV), the number of dropouts, i.e. signals with insufficient quality to be analysed, is normally low. In Paper V, the number of dropouts was however more than 50%. Due to the reasons presented in Chapter 2.2 – beyond the scope and control of this paper – a seven-channel bipolar linear array electrode with a 5-mm IED was used. The electrode was at a prototype stage and not pre-gelled. The main reasons for the SEMG dropouts were most probably a high occurrence of insufficient electrode-to-skin contact and short-circuiting.

4.4.4 Motor unit decomposition

A segmentation carried out with sections of variable length has the advantage of containing not too much and not too little data for classifying the segment and was therefore chosen as a segmentation technique in the work reported in this thesis. As mentioned in Chapter 1.5.2, both single-linkage and complete-linkage techniques for the classification of segments may have limitations in the context of decomposing intramuscular EMG signals acquired from muscle contractions of a long duration. To solve this, both methods were used. As in complete-linkage, we used templates, but these were based on the MUAP shapes from a time window (±3 s) around a specific segment. The templates thus changed somewhat with time, a change that was possible to inspect after the complete classification to evaluate their correctness.

To evaluate the classification performance of a newly developed decomposition program and investigate whether it was less time consuming, 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 misclassifications and was less user-friendly than the program formerly used. A MATLAB-based interface program was developed for presentation and editing of data. With these improvements, the EMG-LODEC software was judged to be a suitable alternative for prolonged recordings, at least when classification rate levels are not crucial.

As shown in the results reported in Papers I-III, the classification rates of the segmented intramuscular signals were primarily between 85 and 95%. The aims of Papers I-III did not require a 100% classification rate; an incomplete decomposition introduces an underestimation of the MU activity, which does not hazard the current findings of MUs with continuous and sustained activity. In the study described in Paper IV, the classification rates were between 72 and 90%. MU doublets may therefore have been missed in the decomposition analysis. However, the comparison between single and double clicks is judged to be relevant since the analysis was blinded for click type.

A critical item is whether any misclassifications occurred in favour of 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 and to reject suspected misclassifications, as in Paper IV. For Papers I-III, this would however have required extremely extensive efforts when prolonged workloads were to be analysed. To achieve a reasonable analysis workload and still obtain data satisfactorily examined for misclassifications, a number of time periods were chosen for each test sequence as random samples for manual analysis.

4.4.5 Choice of muscle regions

As mentioned in the introduction, work-related musculoskeletal disorders are common in the neck/shoulder region and the upper extremities among computer workers. Far from all musculoskeletal disorders are located in the muscle tissues. As concerns the neck/shoulder region, however, an extensive review study of epidemiological findings (Bernard et al. 1997) inferred consistently high odds ratios for TNS associated with static postures or static loads. Moreover, a recent study by Juul-Kristensen et al. (2005) reported that trapezius myalgia and TNS were the two most frequent clinical diagnoses among elderly female computer users with self-reported neck/shoulder complaints. According to a study by Ranney et al. (1995) of 146 female workers in highly repetitive industries, neck/shoulder muscular disorders are most commonly located in the trapezius muscles. There are also indications of muscular disorders in the upper extremities (Ljung et al. 1999; Ranney et al. 1995), although to a lower extent than in the neck/shoulder region. In the latter study, it is further reported that the forearm extensor muscles are major sites of muscular disorders in the upper extremities.

On the basis of these data, it was decided to aim the present study at investigating muscular activity and to choose the left/right upper trapezius and the right EDC as major muscle sites. In Paper IV, the FCU muscle was included to facilitate comparisons with other studies, and as a representation of the flexor side musculoskeletal system, which is a less reported region in the case of WMSDs (Ranney et al. 1995; Gerr et al. 2002).

4.4.6 SEMG crosstalk in forearm muscles

In the anatomy of the forearm, several muscles are neighbours to the EDC and FCU muscles. Close to the EDC muscle are, for example, the extensor carpi radialis brevis and extensor carpi ulnaris muscles. These muscles primarily extend the wrist and adduct/abduct the hand, while the EDC muscle is primarily a wrist- and finger-extensor (Moore 1985). The flexor digitorum superficialis and the more deeply located flexor digitorum profundus are the two largest muscles surrounding the FCU muscle. While the FCU muscle primarily flexes the wrist and adducts the hand, the former two primarily flex the fingers, excluding the thumb (Moore 1985). Thus, many of the major surrounding muscles have at least partly different functions than those of the EDC and FCU muscles, respectively. Due to the proximity of these muscles, crosstalk can still be expected to occur in the recorded EDC and FCU SEMG signals. In a study by Mogk and Keir (2003), the crosstalk between the forearm extensor and flexor muscle recording sites was reported to be less than 2% during both pinch and grasp tasks, while the corresponding figures within neighbouring extensor and flexor sites were 50 and 60%, respectively. Thus, it would be reasonable to regard the recorded EDC and FCU SEMG signals as forearm extensor and flexor muscle group signals, respectively, with no or very limited extensor versus flexor crosstalk. This has however no implications for the conclusions drawn in this thesis.

4.4.7 Self-reported complaints vs. muscular disorders

The neck/shoulder complaints reported in the NMQ questionnaire used in Paper V are not necessarily related to disorders located in muscle tissue. However, a clinical investigation of the subject group studied reported that trapezius myalgia and TNS were the two most frequent clinical diagnoses among cases (Juul-Kristensen et al. 2005). In total, muscle disorders could be diagnosed in 60% of the cases and in only 7% of the non-cases. Thus, a relation between self-reported neck/shoulder complaints and muscular disorders is substantiated in the subject group studied.

4.4.8 Average workload levels

Median SEMG RMS levels are presented in Table 3 for the muscles studied.

Table 3. Median SEMG RMS levels [%MVE] for the muscles studied in Papers I-V.

	Median SEMG RMS [%MVE]				
	Paper I	**Paper II**	**Paper III**	**Paper IV**	**Paper V**
Trapezius non-mouse side				4.0	8.1 (typing) 6.6 (editing) 1.2 (precision) 1.9 (stress)
Trapezius mouse side	5.1		8.2	4.8	9.7 (typing) 8.5 (editing) 2.1 (precision) 1.8 (stress)
EDC mouse side		9.7*		11.0	
FCU mouse side				1.3	

* For the prolonged static task

Studies of muscular activity among computer workers performing regular work at their workplace have reported median trapezius activities of 3.3 and 3.6 %MVE on the non-mouse and the mouse side, respectively, among female office assistants (Blangsted et al. 2003), and of approximately 2 and 4 %MVE among CAD operators (Jensen et al. 1998, 1999). EVA 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, indicating a high degree of static workload. Furthermore, the median EDC activity was here approximately 6 %MVE. Laboratory studies involving mouse work tasks have reported median EDC activities of approximately 8 %MVE during low mental, time and precision demands (Birch et al. 2000c), 17 %MVE during high-precision work (Aarås and Ro 1997) and 8-10 %MVE during various mouse tasks and precision demands (Laursen et al. 2001). The latter study also reported a median activity of approximately 4-6 %MVE in the right FCR muscle. Thus the average trapezius and EDC levels for the work tasks in Papers I-IV, with the possible exception of one subject in Paper III, correspond to findings in previous studies involving computer work. Furthermore, the typing and editing tasks chosen in Paper V may represent rather intensive computer tasks.

4.5 Morphological changes and pain generation

Although not the focus of this thesis, the issues treated in this chapter are important for building of knowledge about the pathogenesis of muscle pain. As mentioned in Chapter 1.3.5, there is still uncertainty as to whether and in which ways selective muscle fibres 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. Animal studies by Lexell et al. (1992, 1993) may provide some information. They studied the degeneration process in a rabbit extensor digitorum longus muscle for nine days of continuous electrical stimulation with pulse trains at frequencies between 1.25 and 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.

As indicated in Chapter 1.3.5, the findings of mitochondrial disturbances and reduced capillarisation in women may, together with the present findings of continuous and sustained MU activity, support the theory that prolonged low-level workloads and psychological stress lead to localised muscle cell ischemia and lactic acid evoked muscle pain, as described by Eriksen (2004). A study of trapezius muscle microcirculation in patients suffering from chronic myalgia showed that the patients showed consistently lower local blood flow in the most painful side of the trapezius than in the opposite side (Larsson et al. 1999). The differences were statistically significant at low contraction intensities. A study of interstitial changes in the trapezius muscle during 20 minutes of repetitive low-force work showed an increase in muscle lactate and an accumulation of metabolites in the upper trapezius muscle, in spite of a muscle activity level below 10 %MVC (Rosendal 2004). Rosendal also demonstrated that work-related trapezius myalgia was associated with locally increased anaerobic metabolism – and increased levels of substances potentially activating peripheral nociceptive processes – even though a reduced local blood flow response could not be seen in the myalgic subjects, as previously presented by Larsson et al. (1999). The present findings of reduced trapezius muscle rest among pain-afflicted subjects suggest that there is a risk that activity-based nociceptive processes – local and/or peripheral – will be maintained, especially during stressful working conditions. There is further support for a maintained nociceptive process in previous findings that neither fatigue (Olsen et al. 2001b) nor experimentally evoked muscle pain (Birch et al. 2000a; Sohn et al. 2000) seem to alter MU activity properties, except for decreased MU firing rate (Sohn et al. 2000; Farina et al. 2004, 2005) and increased twitch force (Sohn et al. 2004). A prolonged pain experience may change the CNS interpretation of muscle spindle signals into indications of pain, i.e. a sensitisation or "memorisation" of the pain (Hagberg 1996). Thus the development of chronic muscle pain may not necessarily be connected to irreversible fibre injuries visible in biopsies but may also be present in apparently uninjured tissues. This could explain the diversity of reported morphological differences between myalgic and pain-free muscles.

A proposed pathway between computer workloads and chronic muscle pain, based on the model proposed by Winkel and Westgaard (1992), is schematically described in Figure 10. In many aspects, this pathway independently resembles the conclusions given in a recent review article by Visser and van Dieën (2005).

Computer work is often of a prolonged, monotonous character with low physical demands. These external exposures can lead to an internal exposure of prolonged low-level muscular activity with few periods of muscle rest. Computer work is also often characterised by the presence of psychological stress. This exposure primarily lead to an internal exposure of induced mental strain and secondarily to prolonged low-level muscular activity with few periods of muscle rest.

As indicated in Papers I-III, *prolonged low-level muscular activity and few periods of muscular rest can lead to continuous and sustained activity of selective MUs*. As a reaction to the induced mental strain, sympathetic nerve activity may be increased, leading to arterial vasoconstriction and reduced capillary flow (Bear et al. 2001; Hansen 2002). Since the muscular activity is of a low-level character, this sympathetic vasoconstriction can be preserved (Hansen 2002). That is, *a combination of low-level muscular activity and induced mental strain can lead to prolonged vasoconstriction*. Furthermore, during low-level muscular activity, the K^+ concentration is maintained close to the resting level (Sjøgaard 1996). Release of intracellular K^+ is one important feedback mechanism in fatigue (Sjøgaard and Søgaard 1998). That is, *low-level muscular activity can lead to an absence of muscular fatigue perception*.

The continuous and sustained MU activity may constitute, *together* with the prolonged vasoconstriction, a risk for localised ischemia in selective muscle fibres. Localised ischemia may, via mitochondrial deficiencies, lead to ATP insufficiency and lactic acid evoked muscle pain (Eriksen 2004). An insufficiency of ATP may also affect the homeostasis of Ca^{2+} released from the sarcoplasmic reticulum during the muscle fibre excitation-contraction phase (Sjøgaard and Søgaard 1998), leading to skeletal muscle damage (Jackson et al. 1984; Gissel 2000). Thus, *the combination of continuous, sustained MU activity and prolonged vasoconstriction may, via an acutely impaired energy metabolism for selective muscle fibres, lead to a production of nociceptives and acute muscle pain*.

Two pathways to chronic pain are suggested, in the case that the workload described above is prolonged. First, there is a risk that an acute pain sensation is prolonged, especially as a perception of muscular fatigue may not be present. Eventually, the *prolonged acute pain sensation can, via CNS pain sensitisation, turn into a chronic pain behaviour* (Hagberg 1996), which does not necessarily need pain stimuli to be maintained. Second, a prolonged workload can also lead to a growth of type I muscle fibres without increased capillary supply, as inferred by Hägg (2000). This is supported by findings of deteriorated microcirculation of blood through specific muscle fibres (Lindman 1992; Larsson et al. 1998, 1999, 2004) in myalgic trapezius muscles. Rosendal (2004) demonstrated that trapezius myalgia was associated with locally increased anaerobic metabolism – and increased levels of substances potentially activating peripheral nociceptive processes. Thus, *a prolonged workload may, through type I fibre growth and deteriorated microcirculation, lead to a chronic impairment of energy metabolism in selected muscle fibres, production of nociceptives and chronic muscle pain*.

Finally, a chronic pain may induce feedback loops that potentially aggravate muscle pain further. As supported by Paper V, *musculoskeletal complaints may increase the motor response to psychological stress, decreasing the muscle rest.*

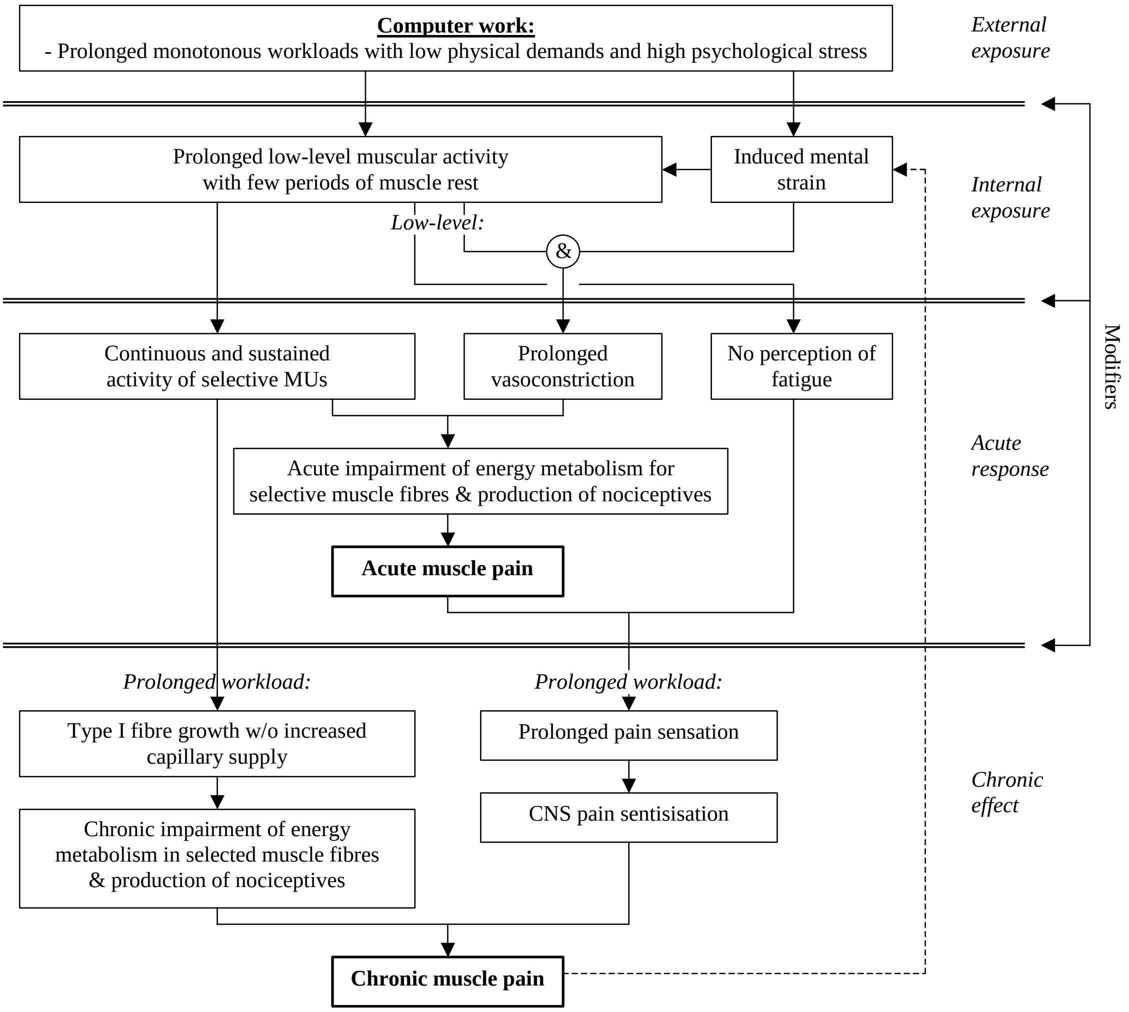

Figure 10. Proposed pathway between computer work and chronic muscle pain. Double lines indicate areas susceptible to modifiers, e.g. individual factors. The dashed line indicates a feedback loop.

5 Conclusions

The main aim of this thesis was to investigate whether muscular activity patterns during tasks characterising computer work are consistent with the Cinderella hypothesis on selective MU overuse.

First, the results of this thesis showed a prevalence of continuous and sustained MU activity in the trapezius muscle and the EDC finger/wrist extensor muscle during standardised low-level work tasks simulating computer work. These results support the Cinderella hypothesis on a selective overuse of specific low-threshold MUs in the context of computer work. Although not the focus of this thesis, it is, however, uncertain *how long* a continuous activity or what firing pattern is needed for muscle cells to become overused and sense pain. Only a minority of the MUs showed a continuous and sustained activity. Many others were intermittently active, which may be a result of MU substitution. Some subjects showed continuously active MUs while others did not, and subjects who showed continuous MU activity in one specific task or muscle often also showed this behaviour in another task or muscle. This could be due to inter-individual differences but must be more thoroughly investigated in further research.

Second, the results did show the existence of MU double firings in the EDC muscle during both single clicking and double clicking a computer mouse. There were no implications that double clicks constitute a higher risk for the generation of MU doublets than do single clicks. For both the trapezius and the EDC muscles, the overall muscle activity levels instead indicated the opposite. It could also be discussed whether the existence of MU doublets during mouse work constitutes a risk for WMSDs, compared to the prolonged static and continuous workloads normally taking place during computer work.

Third, subjects with self-reported neck/shoulder complaints tended to show less muscle rest as compared to those without complaints during a short-term standardised stress task. No differences were shown for other tasks performed (typing, editing and mouse precision work). The results indicate an increased trapezius motor response to psychological stress among subjects with vs. without neck/shoulder complaints. It is suggested that stressful working conditions – especially in subjects with neck/shoulder complaints – increase the risk for muscular overuse, supporting the Cinderella hypothesis in the context of an activity-based pathogenesis and maintenance of myalgia.

In summary, the results give support to the Cinderella hypothesis on an MU activity-based development of myalgia in the context of computer work and indicate that stressful working conditions increase the risk for muscular overuse. Further investigations are needed on the underlying mechanisms of MU substitution and inter-individual MU activity differences, and of the causal pathways between continuous and sustained MU activity, selective MU overuse and chronic pain.

6 Further research

The underlying mechanisms and importance of MU substitution should be further investigated. This subject has previously been addressed by e.g. Westgaard and De Luca (1999, 2001), Westgaard and Westad (2003) and Westad et al. (2003), and is a work that needs further progress. There is particularly a lack of understanding of why some MUs are continuously active while others seem to fire intermittently, i.e. of intra-individual differences.

Further research is also needed on the existence of and mechanisms of inter-individual differences in continuous MU activity. A comparative study of MU activity differences between subjects and between repeated measurements in the same subjects is in progress. The purpose is to investigate the ability to generalise MU activity results, decomposed from intramuscular EMG data. This methodological study has the prospect to increase knowledge about the existence of inter-individual MU activity differences in a healthy subject group, although less about the underlying mechanisms.

Finally, important questions that are still open are how long a continuous activity or what firing pattern is needed for muscle cells to sensitise pain, and how the pathway to chronic pain behaviour works. Research in these questions will require extensive cooperation between various disciplines, and findings of causal relationships address a call for longitudinal studies.

References

Aarås A, Ro O (1997) Workload when using a mouse as an input device. Int J Hum Comp Interact 9: 105-118

Adam A, De Luca C (2003) Recruitment order of motor units in human vastus lateralis muscle is maintained during fatiguing contractions. J Neurophysiol 90: 2919-2927

Barry DT (1987) Acoustic signals from frog skeletal muscle. Biophys J 51: 769-773

Basmajian JV, De Luca CJ (1985) Muscles alive. Their functions revealed by electromyography. Williams & Wilkins, Baltimore

Bawa P, Calancie B (1983) Repetitive doublets in human flexor carpi radialis muscle. J Physiol (Lond) 339: 123-132

Bear MF, Connors BW, Paradiso MA (2001) Neuroscience - Exploring the Brain. Lippincott Williams & Wilkins, Philadelphia, PS

Beckman JS, Koppenol WH (1996) Nitric oxide, superoxide and peroxynitrite: the good, the bad, and the ugly. Am J Physiol 271: C1424-C1437

Bergenheim M (2003) Neurophysiological mechanisms behind work-related myalgia: effects on proprioception and balance. In: Johansson H, Windhorst U, Djupsjöbacka M, Passatore M (eds) Chronic Work-Related Myalgia - Neuromuscular Mechanisms behind Work-Related Chronic Muscle Pain Syndromes. Gävle University Press, Umeå, pp 155-161

Bernard BP, Putz-Anderson V, Burt SE, Cole LL, Fairfield-Estill C, Fine LJ, Grant KA, Gjessing C, Jenkins L, Hurrell JJ, Nelson N, Pfirman D, Roberts R, Stetson D, Haring-Sweeney M, Tanaka S (1997) Musculoskeletal disorders and workplace factors. A critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back. Available at: http://www.cdc.gov/niosh/pdfs/97-141.pdf. DHHS (NIOSH) Publ No 97-141

Birch L, Christensen H, Arendt-Nielsen L, Graven-Nielsen T, Søgaard K (2000a) The influence of experimental muscle pain on motor unit activity during low-level contraction. Eur J Appl Physiol 83: 200-206

Birch L, Graven-Nielsen T, Christensen H, Arendt-Nielsen L (2000b) Experimental muscle pain modulates muscle activity and work performance differently during high and low precision use of a computer mouse. Eur J Appl Physiol 83: 492-498

Birch L, Juul-Kristensen B, Jensen C, Finsen L, Christensen H (2000c) Acute response to precision, time pressure and mental demand during simulated computer work. Scand J Work Environ Health 26: 299-305

Blangsted AK, Hansen K, Jensen C (2003) Muscle activity during computer-based office work in relation to self-reported job demands and gender. Eur J Appl Physiol 89: 352-358

Blangsted AK, Olsen HB, Søgaard K (2001) Motor unit firing behaviour in human trapezius muscle during double clicking of computer mouse. Movement and Sensation, International Symposium Sep 3-6, Cairns, Australia

Blatter BM, Bongers PM (2002) Duration of computer use and mouse use in relation to musculoskeletal disorders of neck or upper limb. Int J Ind Ergonom 30: 295-306

Broman H (1988) Knowledge-based signal processing in the decomposition of myoelectric signals. IEEE Engineering in Medicine and Biology Magazine 7: 24-28

Denny-Brown D, Pennybacker JB (1938) Fibrillation and fascilulation in voluntary muscle. Brain 61: 311-334

Denslow JS (1948) Double discharges in human motor units. J Neurophysiol 11: 209-215

Desmedt JE, Godaux E (1977) Ballistic contractions in man: characteristic recruitment pattern of single motor units of the tibialis anterior muscle. J Physiol (Lond) 264: 673-693

Disselhorst-Klug C, Bahm J, Ramaekers V, Trachterna A, Rau G (2000) Non-invasive approach of motor unit recording during muscle contractions in humans. Eur J Appl Physiol 83: 144-150

Eriksen W (2004) Linking work factors to neck myalgia: the nitric oxide/oxygen ratio hypothesis. Med Hypotheses 62: 721-726

Fallentin N, Jørgensen K, Simonsen EB (1993) Motor unit recruitment during prolonged isometric contractions. Eur J Appl Physiol 67: 335-341

Farina D, Arendt-Nielsen L, Graven-Nielsen T (2005) Experimental muscle pain reduces initial motor unit discharge rates during sustained submaximal contractions. J Appl Physiol 98: 999-1005

Farina D, Arendt-Nielsen L, Merletti R, Graven-Nielsen T (2004) Effect of experimental muscle pain on motor unit firing rate and conduction velocity. J Neurophysiol 91: 1250-1259

Fogleman M, Lewis RJ (2002) Factors associated with self-reported musculoskeletal discomfort in video display terminal (VDT) users. Int J Ind Ergonom 29: 311-318

Forsman M, Birch L, Zhang Q, Kadefors R (2001) Motor-unit recruitment in the trapezius muscle with special reference to coarse arm movements. J Electromyogr Kinesiol 11: 207-216

Forsman M, Kadefors R, Zhang Q, Birch L, Palmerud G (1999) Motor-unit recruitment in the trapezius muscle during arm movements and in VDU precision work. Int J Ind Ergonom 24: 619-630

Forsman M, Zhang Q, Birch L, Palmerud G, Lundberg U, Kadefors R (2000) Motor-unit recruitment in the trapezius muscle during occupationally relevant arm movements, stress included contractions and in VDU work tasks. In: Fostervold KI, Endestad T (eds) At the Gateway to Cyberspace - Ergonomic Thinking in a New Millennium, Proceedings of the Nordic Ergonomic Society (NES) Annual Conference, Oslo, pp 105-108

Frangioni JV, Kwan-Gett TS, Dobrunz LE, McMahon TA (1987) The mechanism of low-frequency sound production in muscle. Biophys J 51: 775-783

Freriks B, Hermens H, Disselhorst-Klug C, Rau G (1999) The recommendations for sensors and sensor placement procedures for surface electromyography. In: Hermens H, Freriks B, Merletti R, Stegeman D, Blok J, Rau G, Disselhorst-Klug C, Hägg G (eds) SENIAM - Deliverable 8 - European Recommendations for Surface ElectroMyoGraphy. Roessingh Research and Development, Enschede, pp 15-54

Garland SJ, Griffin L (1999) Motor unit double discharges: statistical anomaly or functional entity? Can J Appl Physiol 24: 113-130

Gerr F, Marcus M, Ensor C, Kleinbaum D, Cohen S, Edwards A, Gentry E, Ortiz DJ, Monteilh C (2002) A prospective study of computer users: 1. Study design and incidence of musculoskeletal symptoms and disorders. Am J Ind Med 41: 221-235

Gissel H (2000) Ca^{2+} accumulation and cell damage in skeletal muscle during low frequency stimulation. Eur J Appl Physiol 83: 175-180

Graven-Nielsen T, Svensson P, Arendt-Nielsen L (1997) Effects of experimental muscle pain on muscle activity and co-ordination during static and dynamic motor function. Electroencephalogr Clin Neurophysiol 105: 156-164

Griffin L, Garland SJ, Ivanova T (1998) Discharge patterns in human motor units during fatiguing arm movements. J Appl Physiol 85: 1684-1692

Guyton AC (1981) Contraction of Skeletal Muscle. Textbook of Medical Physiology. Saunders, Philadelphia 122-137

Hagberg M (1981) Electromyographic signs of shoulder muscular fatigue in two elevated arm positions. Am J Phys Med 60: 111-121

Hagberg M (1982) Local shoulder muscular strain - symptoms and disorders. J Hum Ergol (Tokyo) 11: 99-108

Hagberg M (1984) Occupational musculoskeletal stress and disorders of the neck and shoulder: a review of possible pathophysiology. Int Arch Occup Environ Health 53: 269-278

Hagberg M (1996) Vilka är mekanismerna för skada? Nacke & skuldra. Att förebygga arbetsrelaterad sjuklighet. Rådet för Arbetslivsforskning, Stockholm 38-59

Hagman M, Wigaeus Tornqvist E, Hagberg M, Hansson Risberg E, Isaksson A, Karlqvist L, Toomingas A (2001) Arbetsförhållanden och hälsa bland datoranvändare. Deskriptiva data från basenkäten i en longitudinell studie av manliga och kvinnliga datoranvändare. In: Wigaeus Tornqvist E (ed) Arbetslivsrapport. ISSN 1400-8211. Arbetslivsinstitutet, Stockholm, pp 1-29

Hansen J (2002) Sympathetic neural control of skeletal muscle blood flow and oxygenation. Dan Med Bull 49: 109-129

Hansson G-Å, Nordander C, Asterland P, Ohlsson K, Strömberg U, Skerfving S, Rempel D (2000) Sensitivity of trapezius electromyography to differences between work tasks - influence of gap definition and normalisation methods. J Electromyogr Kinesiol 10: 103-115

Henneman E, Somjen G, Carpenter DO (1965) Excitability and inhibitability of motoneurons of different sizes. J Neurophysiol 28: 599-620

Holte KA, Westgaard RH (2002) Daytime trapezius muscle activity and shoulder-neck pain of service workers with work stress and low biomechanical exposure. Am J Ind Med 41: 393-405

Hubbard DR, Berkoff GM (1993) Myofascial trigger points show spontaneous needle EMG activity. Spine 18: 1803-1807

Hägg GM (1991) Static work loads and occupational myalgia - a new explanation model. In: Anderson PA, Hobart DJ, Danoff JV (eds) Electromyographical Kinesiology. Elsevier Science, Amsterdam, pp 141-143

Hägg GM (2000) Human muscle fibre abnormalities related to occupational load. Eur J Appl Physiol 83: 159-165

Hägg GM, Åström A (1997) Load pattern and pressure pain threshold in the upper trapezius muscle and psychosocial factors in medical secretaries with and without shoulder/neck disorders. Int Arch Occup Environ Health 69: 423-432

Jackson MJ, Jones DA, Edwards RHT (1984) Experimental skeletal muscle damage: the nature of the calcium-activated degenerative processes. Eur J Clin Invest 14: 369-374

Järvholm U, Palmerud G, Karlsson D, Herberts P, Kadefors R (1991) Intramuscular pressure and electromyography in four shoulder muscles. J Orthop Res 9: 609-619

Jensen C (2003) Development of neck and hand-wrist symptoms in relation to duration of computer use at work. Scand J Work Environ Health 29: 197-205

Jensen C, Borg V, Finsen L, Hansen K, Juul-Kristensen B, Christensen H (1998) Job demands, muscle activity and musculoskeletal symptoms in relation to work with the computer mouse. Scand J Work Environ Health 24: 418-424

Jensen C, Finsen L, Hansen K, Christensen H (1999) Upper trapezius muscle activity patterns during repetitive manual material handling and work with a computer mouse. J Electromyogr Kinesiol 9: 317-325

Jensen C, Westgaard RH (1997) Functional subdivision of the upper trapezius muscle during low-level activation. Eur J Appl Physiol 76: 335-339

Johansson H (2002) Work-related musculoskeletal disorders - state of the art of pathophysiological mechanisms. In: Caldenfors D, Eklund J, Kiviloog L (eds) Proceedings of the 34th Congress of the Nordic Ergonomics Society. Linköping University, Linköping, pp 415-420

Johansson H, Sojka P (1991) Pathophysiological mechanisms involved in genesis and spread of muscular tension in occupational muscle pain and in chronic musculoskeletal pain syndromes: a hypothesis. Med Hypotheses 35: 196-203

Johnson P, McLoone H, Adams E, Arms S (2000) Developing miniature force-sensing technologies for measuring the forces applied to a computer mouse. Proceedings of the Human Factors and Ergonomics Society's 44th Annual Meeting. HFES, Santa Monica, CA, pp 629-632

Joyner MJ, Dietz NM (2003) Sympathetic vasodilation in human muscle. Acta Physiol Scand 177: 239-336

Juel C (2001) Current aspects of lactate exchange: lactate/H^+ transport in human skeletal muscle. Eur J Appl Physiol 86: 12-16

Juul-Kristensen B, Kadefors R, Hansen K, Byström P, Sandsjö L, Sjøgaard G (2005) Clinical signs and physical function in neck and upper extremeties among elderly female computer users. The NEW-study. Eur J Appl Physiol (E-pub ahead of print)

Juul-Kristensen B, Laursen B, Pilegaard M, Jensen BR (2004) Physical workload during use of speech recognition and traditional computer input devices. Ergonom 47: 119-133

Kadefors R, Forsman M, Zoega B, Herberts P (1999) Recruitment of low threshold motor-units in the trapezius muscle in different static arm positions. Ergonom 42: 359-375

Kadefors R, Läubli T (2002) Muscular disorders in computer users: introduction. Int J Ind Ergonom 30: 203-210

Kadi F, Hägg G, Håkansson R, Holmner S, Butler-Browne GS, Thornell L-E (1998a) Structural changes in male trapezius muscle with work-related myalgia. Acta Neuropathol (Berl) 95: 352-360

Kadi F, Waling K, Ahlgren C, Sundelin G, Holmner S, Butler-Bowne GS, Thornell E (1998b) Pathological mechanisms implicated in localized female trapezius myalgia. Pain 78: 191-196

Knardahl S (2002) Psychophysiological mechanisms of pain in computer work: the blood vessel-nociceptor interaction hypothesis. Work and Stress 16: 179-189

Knardahl S, Hendley ED (1990) Association between cardiovascular reactivity to stress and hypertension or behavior. Am J Physiol 259: H248-H257

Körner L, Parker P, Almström C, Herberts P, Kadefors R (1984) The relation between spectral changes of the myoelectric signal and the intramuscular pressure of human skeletal muscle. Eur J Appl Physiol 52: 202-206

Kourinka I, Jonsson B, Kilbom Å, Vinterberg H, Biering-Sørensen F, Andersson G, Jørgensen K (1987) Standardised Nordic questionnaires for the analysis of musculoskeletal symptoms. Appl Ergonom 18: 233-237

Kouzaki M, Shinohara M, Masani K, Fukunaga T (2004) Force fluctuations are modulated by alternate muscle activity of knee extensor synergists during low-level sustained contraction. J Appl Physiol 97: 2121-2131

Kudina LP, Alexeeva NL (1992) Repetitive doublets of human motoneurones: analysis of interspike intervals and recruitment pattern. Electroencephalogr Clin Neurophysiol 85: 243-247

Kumar S (1996) Electromyography in ergonomics. In: Kumar S, Mital A (eds) Electromyography in Ergonomics. Taylor&Francis, London, pp 1-50

Larsson B, Björk J, Elert J, Gerdle B (2000a) Mechanical performance and electromyography during repeated maximal isokinetic shoulder forward flexions in female cleaners with and without myalgia of the trapezius muscle and in healthy controls. Eur J Appl Physiol 83: 257-267

Larsson B, Björk J, Elert J, Lindman R, Gerdle B (2001) Fibre type proportion and fibre size in trapezius muscle biopsies from cleaners with and without myalgia and its correlation with ragged red fibres, cytochrome-c-oxidase-negative fibres, biomechanical output, perception of fatigue, and surface electromyography during repetitive forward flexions. Eur J Appl Physiol 84: 492-502

Larsson B, Björk J, Henriksson KG, Gerdle B, Lindman R (2000b) The prevalences of cytochrome c oxidase negative and superpositive fibres and ragged-red fibres in the trapezius muscle of female cleaners with and without myalgia and of female healthy controls. Pain 84: 379-387

Larsson B, Björk J, Kadi F, Lindman R, Gerdle B (2004) Blood supply and oxidative metabolism in muscle biopsies of female cleaners with and without myalgia. Clin J Pain 20(6): 440-446

Larsson R, Cai H, Zhang Q, Öberg PÅ, Larsson SE (1998) Visualization of chronic neck-shoulder pain: impaired microcirculation in the upper trapezius muscle in chronic cervico-brachial pain. Occup Med 48: 189-194

Larsson R, Öberg PA, Larsson SE (1999) Changes of trapezius muscle blood flow and electromyography in chronic neck pain due to trapezius myalgia. Pain 79: 45-50

Larsson S-E, Bengtsson A, Bodegård L, Henriksson KG, Larsson J (1988) Muscle changes in work-related chronic myalgia. Acta Orthop Scand 59: 552-556

Laursen B, Jensen BR, Garde AH, Jørgensen AH (2002) Effect of mental and physical demands on muscular activity during the use of a computer mouse and a keyboard. Scand J Work Environ Health 28: 215-221

Laursen B, Jensen BR, Ratkevicius A (2001) Performance and muscle activity during computer mouse tasks in young and elderly adults. Eur J Appl Physiol 84: 329-336

Lexell J, Jarvis J, Downham D, Salmons S (1992) Quantitative morphology of stimulation-induced damage in rabbit fast-twitch skeletal muscles. Cell Tissue Res 269: 195-204

Lexell J, Jarvis J, Downham D, Salmons S (1993) Stimulation-induced damage in rabbit fast-twitch skeletal muscles: a quantitative morphological study of the influence of pattern and frequency. Cell Tissue Res 273: 357-362

Lindman R (1992) Chronic trapezius myalgia - a morphological study. In: Åstrand I (ed) Arbete och Hälsa. Arbetslivsinstitutet, Stockholm, pp 1-46

Ljung B-O, Lieber RL, Fridén J (1999) Wrist extensor muscle pathology in lateral epicondylitis. J Hand Surg [Br] 24B: 177-183

Lund JP, Donga R (1991) The pain-adaption model: a discussion of the relationship between chronic musculoskeletal pain and motor activity. Can J Physiol Pharmacol 69: 683-694

Lundberg U, Forsman M, Zachau G, Eklöf M, Palmerud G, Melin B, Kadefors R (2002) Effects of experimentally induced mental and physical stress on trapezius motor unit recruitment. Work and Stress 16: 166-178

Lundervold AJS (1951) Electromyographic investigations of position and manner of working in typewriting. Acta Physiol Scand Suppl 24: 152-164

Madeleine P, Bajaj P, Søgaard K, Arendt-Nielsen L (2001) Mechanomyography and electromyography force relationships during concentric, isometric and eccentric contractions. J Electromyogr Kinesiol 11: 113-121

Madeleine P, Jørgensen LV, Søgaard K, Arendt-Nielsen L, Sjøgaard G (2002) Development of muscle fatigue as assessed by electromyography and mechanomyography during continuous and intermittent low-force contractions: effects of the feedback mode. Eur J Appl Physiol 87: 28-37

Madeleine P, Lundager B, Voigt M, Arendt-Nielsen L (1998) Sensory manifestations in experimental and work-related chronic neck-shoulder pain. Eur J Pain 2: 251-260

Madeleine P, Lundager B, Voigt M, Arendt-Nielsen L (1999) Shoulder muscle co-ordination during chronic and acute experimental neck-shoulder pain. An occupational pain study. Eur J Appl Physiol 79: 127-140

Madeleine P, Lundager B, Voigt M, Arendt-Nielsen L (2003) The effects of neck-shoulder pain development on sensory-motor interactions among female workers in the poultry and fish industries. A prospective study. Int Arch Occup Environ Health 76: 39-49

Mathiassen SE, Aminoff T (1997) Motor control and cardiovascular responses during isoelectric contractions of the upper trapezius muscle: evidence for individual adaptation strategies. Eur J Appl Physiol 76: 434-444

Mathiassen SE, Hägg GM (1997) Amplitude aspects and functional considerations on surface EMG electrode displacements with particular emphasis on the upper trapezius muscle. In: Hemens H, Freriks B (eds) The State of the Art on Sensors and Sensor Placement Procedures for Surface Electromyography. SEMIAM, Roessingh Research and Development, Enschede, pp 84-95

Mathiassen SE, Turpin-Legendre E (1998) Reduction of isometric shoulder elevation fatigue by periods of increased load. Proceedings of the 3rd International Scientific Conference on Prevention of Work-Related Musculoskeletal Disorders (PREMUS-ISEOH ´98). Finnish Institute of Occupational Health, Helsinki, pp 1

Mathiassen SE, Winkel J (1990) Electromyographic activity in the shoulder-neck region according to arm position and glenohumeral torque. Eur J Appl Physiol 61: 370-379

Mathiassen SE, Winkel J, Hägg GM (1995) Normalization of surface EMG amplitude from the upper trapezius muscle in ergonomic studies - a review. J Electromyogr Kinesiol 5: 197-226

Matre D, Knardahl S (2003) Sympathetic activity does not reduce proprioceptive acuity in humans. Acta Physiol Scand 178: 261-268

McComas AJ (1996) Motor units. Skeletal muscle. Form and Function. Human Kinetics, Champaign, IL 183-202

McLean L, Goudy N (2004) Neuromuscular response to sustained low-level muscle activation: within- and between-synergist substitution in the triceps surae muscles. Eur J Appl Physiol 91: 204-216

McNulty WH, Gevirtz RN, Hubbard DR, Berkoff GM (1994) Needle electromyographic evaluation of trigger point response to a phychological stressor. Psychophysiol 31: 313-316

Merletti R, Benevenuti F, Doncarli C, Disselhorts-Klug C, Ferrabone R, Hermens HJ, Kadefors R, Läubli T, Orizio C, Sjøgaard G, Zazula D (2004) The European project 'Neuromuscular assessment in the elderly worker' (NEW): achievements in electromyogram signal acqusition, modelling and processing. Med Biol Eng Comput 42: 429-431

Mogk JPM, Keir PJ (2003) Crosstalk in surface electromyography of the proximal forearm during gripping tasks. J Electromyogr Kinesiol 13: 63-71

Moncada S, Erusalimsky JD (2002) Does nitric oxide modulate mitochondrial energy generation and apotosis? Nature Reviews Molecular Cell Biology 3: 214-220

Moore KL (1985) The Forearm or Antebrachium. Clinically Oriented Anatomy. Williams & Wilkins, Baltimore, US 691-733

Mork PJ, Westgaard RH (2004) The association between nocturnal trapezius muscle activity and shoulder and neck pain. Eur J Appl Physiol 92: 18-25

Mortara DW (1977) Digital filters for ECG signals. Computers in cardiology: Annual Conference of Computers in Cardiology. IEEE Press, Long Beach, CA, pp 511-514

Nordander C, Hansson G-Å, Rylander L, Asterland P, Unge Byström J, Ohlsson K, Balogh I, Skerfving S (2000) Muscular rest and gap frequency as EMG measures of physical exposure: the impact of work tasks and individual related factors. Ergonom 43: 1904-1919

Olsen HB, Blangsted AK, Søgaard K (2001a) Motor unit firing behaviour in human trapezius muscle during double clicking of computer mouse. In: Sandsjö L, Kadefors R (eds) The 2nd PROCID Symposium, Prevention of Muscle Disorders in Computer Users: Scientific Basis and Recommendations. National Institute for Working Life/West, Göteborg, pp 233-239

Olsen HB, Christensen H, Søgaard K (2001b) An analysis of motor unit firing pattern during sustained low force contraction in fatigued muscle. Acta Physiol Pharmacol Bulg 26: 73-78

Orizio C (1993) Muscle sound: bases for the introduction of a mechanomyographic signal in muscle studies. Crit Rev Biomed Eng 21: 201-243

Palmerud G, Kadefors R, Sporrong H, Järvholm U, Herberts P, Högfors C, Peterson B (1995) Voluntary redistribution of muscle activity in human shoulder muscles. Ergonom 38: 806-815

Palmerud G, Sporrong H, Herberts P, Kadefors R (1998) Consequences of trapezius relaxation on the distribution of shoulder muscle forces: an electromyographic study. J Electromyogr Kinesiol 8: 185-193

Partanen VSJ, Lang AH (1978) An analysis of double discharges in the human elecromyogram. J Neurol Sci 36: 363-375

Passatore M, Roatta S (2003) Sympathetic nervous system: interaction with muscle function and involvement in motor control. In: Johansson H, Windhorst U, Djupsjöbacka M, Passatore M (eds) Chronic Work-Related Myalgia - Neuromuscular Mechanisms behind Work-Related Chronic Muscle Pain Syndromes. ISBN: 91-974948-0-1. Gävle University Press, Umeå, pp 243-263

Pedersen J, Lönn J, Hellström F, Djupsjöbacka M, Johansson H (1999) Localized muscle fatigue decreases the acuity of the movement sense in the human shoulder. Med Sci Sports Exerc 31: 1047-1052

Pedersen J, Sjölander P, Wenngren BI, Johansson H (1997) Increased intramuscular concentration of bradykinin increases the static fusimotor drive to muscle spindles in neck muscles of the cat. Pain 70: 83-91

Person RS (1974) Rhythmic activity of a group of human motoneurones during voluntary contraction of a muscle. Electroencephalogr Clin Neurophysiol 36: 585-595

Piper H (1912) Über den willkürlichen muskeltetanus. Archiv für Physiologie 119: 301-338

Pozzo M, Bottin A, Ferrabone R, Merletti R (2004) Sixty-four channel wearable acqusition system for long-term surface electromyogram recording with electrode arrays. Med Biol Eng Comput 42: 455-466

Ranney D, Wells R, Moore A (1995) Upper limb musculoskeletal disorders in highly repetitive industries: precise anatomical physical findings. Ergonom 38: 1408-1423

Ray CA, Hume KM, Shortt TL (1997) Skin sympathetic outflow during head-down neck flexions in humans. Am J Physiol 273: R1142-R1146

Rosendal L (2004) Interstitial changes in trapezius muscle during repetitive low-force work. PhD Thesis. National Institute of Occupational Health, Copenhagen 1-65

Rossi S, della Volpe R, Ginanneschi F, Ulivelli M, Bartalini S, Spidalieri R, Rossi A (2003) Early somatosensory processing during tonic muscle pain in humans: relation to loss of proprioception and motor 'defensive' strategies. Clin Neurophysiol 114: 1351-1358

Sandsjö L, Larsman P, Voellenbroek-Hutten MMR, Läubli T, Juul-Kristensen B, Klipstein A, Hermens H, Søgaard K (2005) Comparative assessment of study groups of elderly female computer users from four European countries: questionnaires used in the NEW study. Eur J Appl Physiol (E-pub ahead of print)

Sandsjö L, Melin B, Rissén D, Dohns I, Lundberg U (2000) Trapezius muscle activity, neck and shoulder pain, and subjective experiences during monotonous work in women. Eur J Appl Physiol 83: 235-238

SCB (2003) The work environment 2003, AM 68 SM 0401. ISSN 0082-0237. Sveriges Officiella Statistik. Arbetsmiljöverket, Örebro, pp 1-225

SCB (2005) Work-Related Disorders 2004, AM 43 SM 0501. ISSN 0082-0237. Sveriges Officiella Statistik. Arbetsmiljöverket, Örebro, pp 1-98

Schleifer LM, Ley R (1994a) End-tidal CO_2 as an index of psycho-physiological activity during VDT data-entry work and relaxation. Ergonom 37: 245-254

Schleifer LM, Ley R (1994b) End-tidal CO2 as an index of psychophysiological activity under high and low data-entry workload demands. Proceedings of the Inaugural Meeting of the International Society for the Advancements of Respitatory Psychophysiology, Saint Flour, France

Schleifer LM, Ley R, Spalding TW (2002) A hyperventilation theory of job stress and musculoskeletal disorders. Am J Ind Med 41: 420-432

Shortt TL, Ray CA (1997) Sympathetic and vascular responses to head-down neck flexion in humans. Am J Physiol 272: H1780-H1784

Sjøgaard G (1996) Potassium and fatigue: the pros and cons. Acta Physiol Scand 156: 257-264

Sjøgaard G, Kiens B, Jørgensen K, Saltin B (1986) Intramuscular pressure, EMG and blood flow during low-level prolonged static contraction in man. Acta Physiol Scand 128: 475-484

Sjøgaard G, Søgaard K (1998) Muscle injury in repetitive motion disorders. Clin Orthodontics Res 351: 21-31

Sjøgaard G, Søgaard K, Finsen L, Olsen HB, Christensen H (2001) Doublets in motor unit activity of human forearm muscle during simulated computer work. Acta Physiol Pharmacol Bulg 26: 83-85

Sjøgaard G, Søgaard K, Hermens HJ, Sandsjö L, Läubli T, Thorn S, Vollenbroek-Hutten MMR, Sell L, Christensen H, Klipstein A, Kadefors R, Merletti R (2005) Neuromuscular assessment in Elderly Workers with and without work related shoulder/neck trouble: the NEW-study design and physiological findings. Eur J Appl Physiol (E-pub ahead of print)

Søgaard K, Blangsted AK, Jørgensen LV, Madeleine P, Sjøgaard G (2003) Evidence of long term muscle fatigue following prolonged intermittent contractions based on mechano- and electromyograms. J Electromyogr Kinesiol 13: 441-450

Søgaard K, Christensen H, Fallentin N, Mizuno M, Quistorff B, Sjøgaard G (1998) Motor unit activation patterns during concentric wrist flexion in humans with different muscle fibre composition. Eur J Appl Physiol 78: 411-416

Søgaard K, Sjøgaard G, Finsen L, Olsen HB, Christensen H (2001) Motor unit activity during stereotyped finger tasks and computer mouse work. J Electromyogr Kinesiol 11: 197-206

Sohn MK, Graven-Nielsen T, Arendt-Nielsen L, Svensson P (2000) Inhibition of motor unit firing during experimental muscle pain in humans. Muscle Nerve 23: 1219-1226

Sohn MK, Graven-Nielsen T, Arendt-Nielsen L, Svensson P (2004) Effects of experimental muscle pain on mechanical properties of single motor units in human masseter. Clin Neurophysiol 115: 76-84

Spriet LL, Howlett RA, Heigernauser GJF (2000) An enzymatic approach to lactate production in human skeletal muscle during exercise. Med Sci Sports Exerc 32: 756-763

Stålberg E (1966) Propagation velocity in human muscle fibers in situ. Acta Physiol Scand 70: 1-112

Stashuk D (2001) EMG signal decomposition: how can it be accomplished and used? J Electromyogr Kinesiol 11: 151-173

Stroop JR (1935) Interference in serial verbal reactions. J Exp Psychol 18: 643-661

Tamaki H, Kitada K, Akamine T, Murata F, Sakou T, Kurata H (1998) Alternate activity in the synergistic muscles during prolonged low-level contractions. J Appl Physiol 84: 1943-1956

van Cutsem M, Duchateau J, Hainaut K (1998) Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. J Phys E Sci Instr 513: 295-305

van Dieën JH, Oude Vrielink HHE, Toussaint HM (1993) An investigation into the relevance of the pattern of temporal activation with respect to erector spinae muscle endurance. Eur J Appl Physiol 66: 70-75

Vasseljen O Jr, Westgaard RH (1995) A case-control study of trapezius muscle activity in office and manual workers with shoulder and neck pain and symptom-free controls. Int Arch Occup Environ Health 67: 11-18

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: 284-290

Visser B, van Dieën JH (2005) Pathophysiology of upper extremity muscle disorders. J Electromyogr Kinesiol (E-pub ahead of print)

Waersted M, Eken T, Westgaard RH (1996) Activity of single motor units in attention-demanding tasks: firing pattern in the human trapezius muscle. Eur J Appl Physiol 72: 323-329

Wahlström J, Hagberg M, Toomingas A, Wigaeus Tornqvist E (2004) Perceived muscular tension, job strain, physical exposure and associations with neck pain among VDU users; a prospective cohort study. Occup Environ Med 61: 523-528

Wahlström J, Lindegård A, Ahlborg Jr G, Ekman A, Hagberg M (2003) Percieved muscular tension, emotional stress, psychological demands and physical load during VDU work. Int Arch Occup Environ Health 76: 584-590

Wellig PT (2000) Zerlegung von langzeitelektromyogrammen zur prävention von arbeitsbedingten muskelschäden. Series in signal and information processing. Hartung-Gorre, Konstanz, pp 1-194

Wenngren B-I, Pedersen J, Sjölander P, Bergenheim M, Johansson H (1998) Bradykinin and muscle stretch alter contralateral cat neck muscle spindle output. Neurosci Res 32: 119-129

Westad C, Westgaard RH (2001) Reducing the risk for motor unit over-exertion: methods of inducing motor unit substitution. In: Beunk-Timmers M (ed) Proceedings of the Fourth International Scientific Conference on Prevention of Work-Related Musculoskeletal Disorders (PREMUS). Nicolaes Tulp Institute, Amsterdam, pp 61.

Westad C, Westgaard RH, De Luca CJ (2003) Motor unit recruitment and derecruitment induced by brief increase in contraction amplitude of the human trapezius muscle. J Physiol (Lond) 552: 645-656

Westgaard RH, De Luca CJ (1999) Motor unit substitution in long-duration contractions of the human trapezius muscle. J Neurophysiol 82: 501-504

Westgaard RH, De Luca CJ (2001) Motor control of low-threshold motor units in the human trapezius muscle. J Neurophysiol 85: 1777-1781

Westgaard RH, Westad C (2003) Trapezius motor unit firing in an ergonomic perspective: effects of force amplitude and force variation. Proceedings of the XVth Triennal Congress of the International Ergonomics Association, August 24-29. The Ergonomics Society of Korea, Seoul, pp 75-78

Wigaeus Tornqvist E, Eriksson N, Bergqvist U (2000) Dator- och kontorsarbetsplatsens fysiska och psykosociala arbetsmiljörisker. In: Marklund S (ed) Arbetsliv och hälsa. Arbetslivsinstitutet, Stockholm, pp 235-260

Winkel J, Westgaard RH (1992) Occupational and individual risk factors for shoulder-neck complaints: Part II – The scientific basis (literature review) for the guide. Int J Ind Ergonom 10: 85-104

Zennaro D, Läubli T, Krebs D, Klipstein A, Krueger H (2003) Continuous, intermitted and sporadic motor unit activity in the trapezius muscle during prolonged computer work. J Electromyogr Kinesiol 13: 113-124

Zennaro D, Läubli T, Krebs D, Krueger H, Klipstein A (2004) Trapezius motor unit activity in symptomatic participants during finger tapping using properly and improperly adjusted desks. Hum Factors 46: 252-266

Zennaro D, Wellig P, Moschytz GS, Läubli T, Krueger H (2001) A decomposition software package for the decomposition of long-term multi-channel electromyographic signals. Proceedings of the 23rd Annual IEEE Conference, Istanbul

Zipp P (1982) Recommendations for the standardization of lead positions in surface electromyography. Eur J Appl Physiol 50: 41-54

Zwarts MJ, Stegeman DF (2003) Multichannel surface EMG: basic aspects and clinical utility. Muscle Nerve 28: 1-17