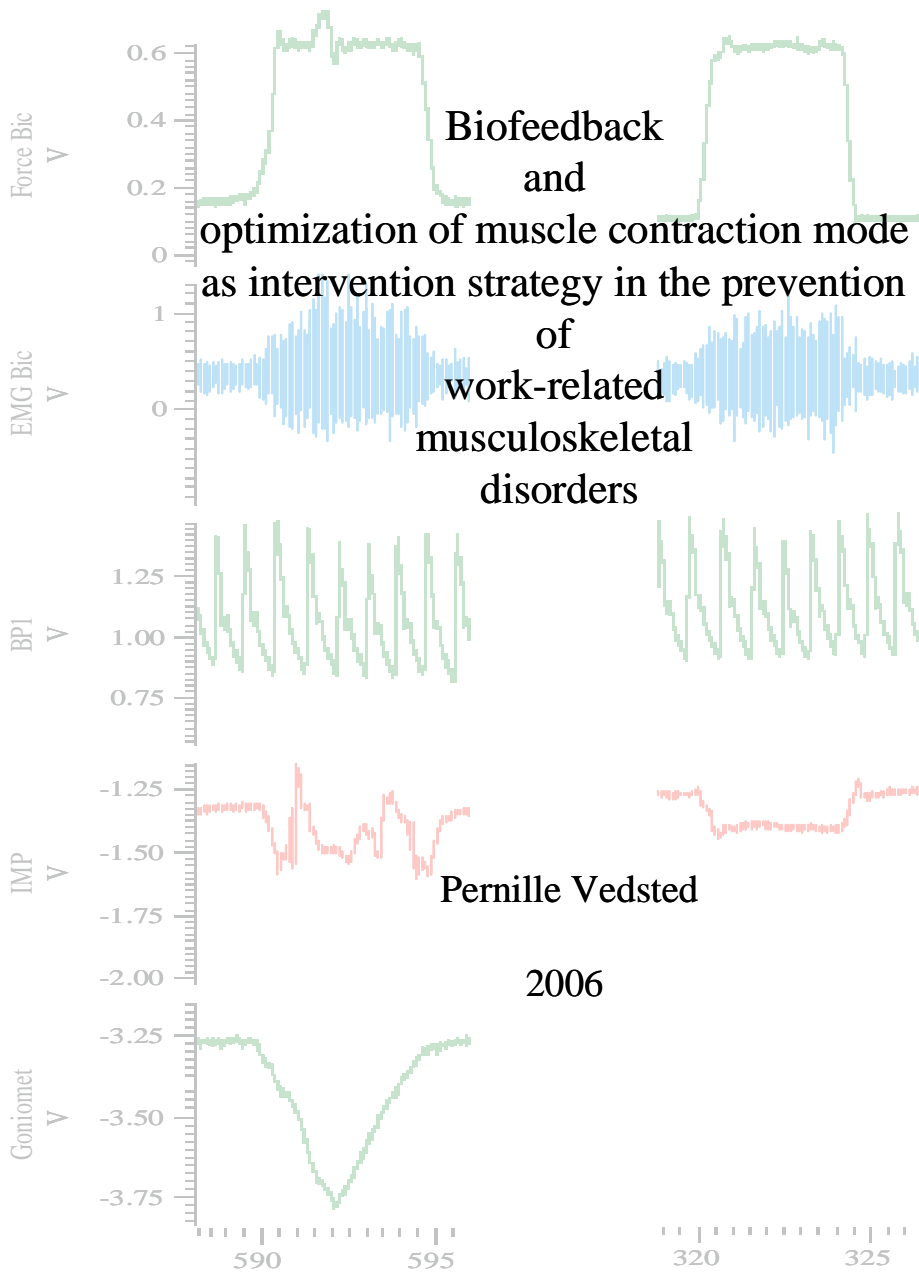




PhD Thesis



Preface

The present PhD thesis has been accomplished at the National Institute of Occupational Health, Copenhagen, Denmark, with enrollment at the Faculty of Health Sciences, University of Southern Denmark. Main supervision was provided by Professor Gisela Sjøgaard, dr. med., National Institute of Occupational Health, Copenhagen. Associate Professor, Klavs Madsen, Ph.D., Institute of Sport Science and Clinical Biomechanics, University of Southern Denmark, provided project supervision. All experiments were conducted at the National Institute of Occupational Health, Copenhagen, Denmark, who also provided laboratory facilities together with all experimental equipment.

The studies presented in the thesis were approved by the ethical committee of Copenhagen (KF 01-043/03) or Vejle/Fyn (no. 19990062) and conducted in conformity with the declaration of Helsinki. The National Institute of Occupational Health, Copenhagen, Denmark, financially supported the PhD project. Further, *study I* was supported by grants from The Danish Research Foundation, The medical Research Council (grant no. 9700565), and The European Community shared-cost RTD actions (QRLT 2000 00139) “*Neuromuscular Assessment in Elderly Workers*” (NEW). *Study II* and *III* were undertaken within the project *NEW* with partial financial support from the EC within the RTD action (QRLT 2000 00139).

Copenhagen, February 21st, 2006

Pernille Vedsted

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PAPER I

PAPER II

PAPER III

List of papers

The present thesis is based on the following 3 papers that will be referred to in the text by their roman numerals.

Paper I

Vedsted P, Sjøgaard K, Blangsted AK, Madeleine P, & Sjøgaard G. Biofeedback effectiveness to reduce upper limb muscle activity during computer work is muscle specific and time pressure depended. (Submitted)

Paper II

Vedsted P, Blangsted AK, Sjøgaard K, Orizio C, & Sjøgaard G. Muscle tissue oxygenation, pressure, electrical, and mechanical responses during dynamic and static voluntary contractions. *Eur J Appl Physiol* 96, 165–177, 2006

Paper III

Blangsted AK, Vedsted P, Sjøgaard G, & Sjøgaard K. Intramuscular pressure and tissue oxygenation during low force static contractions are not underlying muscle fatigue evidenced by electro- and mechanomyography. *Acta Physiol Scand* 183, 379–388, 2005

Summary (English)

Introduction

Elevated static muscle activity has been identified as one of the major risk factors in the development of work-related musculoskeletal disorders (WRMD). Therefore, it is generally accepted in the occupational literature that dynamic contractions are preferable to static contractions in the prevention of musculoskeletal disorders. However, according to basic muscle physiological findings the total metabolic energy consumption rate and decrease in energy stores have shown to be larger when a given corresponding force profiles are developed during dynamic compared to static contractions. Thus, opposing hypothesis regarding preferable contraction modes exist.

The overall aim of the thesis is to identify possible intervention strategies in the workplace that may prevent the development of WRMD due to repetitive low-force work. The specific aims were: 1) to minimize unnecessary muscle activity through biofeedback during standardized computer work under various working conditions (*Study I*); 2) to determine the optimal muscle activation mode when performing low-force activities based on minimal electrical, mechanical, and metabolic responses (*Study II and III*).

Methods

Study I: Subjects (n=11) performed standardized computer work during two different working conditions (*time pressure/no time pressure*) with or without biofeedback. The biofeedback was given from two different muscles (*right m. trapezius (TRA) or right m. extensor digitorum communis (EDC)*) through two different modes (*visual or auditory*) by the use of electromyography (EMG) or mechanomyography (MMG) as the biofeedback source. Outcome measure was EMG from right and left TRA and EDC.

Study II: Subjects (n=8) performed static and dynamic low-force contractions with identical time-tension products as elbow flexion for 1 min in 3 working modes. The working sessions were; 1) sustained static session (SST) with a 1 min sustained static contraction at 5 (LOW) and 10 (HIGH) %MVC, 2) dynamic session (DYN) as a 20° elbow movement with 2 s concentric phase, 2 s eccentric phase (mean movement velocity: 10 degrees/s), and 4 s resting period following each contraction, and 3) intermittent static session (IST) with 4 s contraction period followed by a 4 s resting period. DYN and IST resulted in eight contractions for each working mode, and each session type was performed at

two force levels: 10 (LOW) and 20 (HIGH) %MVC. Outcome measures were EMG, MMG, intramuscular pressure (IMP), and muscle tissue oxygenation (TO₂) from m. biceps brachii.

Study III: Subjects (n=7) performed sustained static elbow flexion at 10 %MVC for 10 min. Test contractions of 5% MVC were performed before, and after 10 min, and 30 min of recovery. Outcome measures were EMG, MMG, IMP, and TO₂ from m. biceps brachii.

Main findings

Study I: Muscle activity was reduced by ~ 30% and ~ 50% in right and left TRA, respectively, when feedback was given from right TRA compared to control (right: 1.7 ± 1.2 vs. 2.4 ± 1.1 %max-EMGrms, $P = 0.07$; left: 1.2 ± 1.2 vs. 2.5 ± 2.1 %max-EMGrms, $P = 0.05$). Activity in the EDC was reduced by ~ 10% when feedback was given from EDC compared to control (8.3 ± 3.4 vs. 9.1 ± 3.1 %max-EMGrms, $P = 0.003$). During time pressure, activity was reduced in right TRA (1.9 ± 1.3 %max-EMGrms, $p=0.08$), left TRA (1.5 ± 1.5 %max-EMGrms, $p=0.09$), and EDC (8.4 ± 3.2 %max-EMGrms, $p=0.002$), during overall feedback compared to control.

Study II: EMGrms and MMGrms were higher during DYN than IST (concentric phase: DYN vs. IST were 14.2 vs. 9.4 and 22.0 vs. 15.9 %max-EMGrms; eccentric phase: in DYN, the MMG was ~1.5 and ~2.0 fold higher than IST at 10 and 20 %MVC, respectively). IMP of the concentric phase in DYN was lower than in IST (2.3 vs. 29.5 and 10.9 vs. 42.0 mmHg in 10 and 20 %MVC, respectively), and a similar picture was seen for eccentric phase. However, no differences were seen in rTO₂ in neither contraction nor resting periods. Mean MMGrms for SST was lower than IST and DYN (LOW: 3.9 ± 0.9 vs. 5.8 ± 1.1 (IST) and 6.7 ± 1.4 (DYN) $\cdot 10^{-3} \cdot \text{m} \cdot \text{s}^{-2}$; and HIGH: 4.2 ± 0.9 vs. 7.0 ± 1.5 (IST) and 8.7 ± 1.8 (DYN) $\cdot 10^{-3} \cdot \text{m} \cdot \text{s}^{-2}$). Mean IMP for SST was higher than DYN (LOW: 16.8 ± 4.9 vs. 8.5 ± 3.9 mmHg; and HIGH: 25.4 ± 7.5 vs. 12.6 ± 4.9 mmHg), which resulted in a 2-fold larger mean reduction of TO₂ in SST than that of DYN and IST.

Study III: During 10%MVC_{10min}, MMGrms increased from 0.04 ± 0.01 to 0.11 ± 0.07 $\text{m} \cdot \text{s}^{-2}$ in the last minute and MMGmpf and EMGmpf decreased from 34.9 ± 8.2 to 21.3 ± 3.8 Hz and from 71.7 ± 10.9 to 61.7 ± 10.0 Hz, respectively. Initially, TO₂ decreased by $6.9 \pm 6.5\%$ of resting level but returned to rest within 1 min. IMP remained constant during the contraction after an initial 4-fold increase from resting level of 12.2 ± 10.4 mmHg.

CONCLUSION 1:

- Biofeedback decreased the prolonged level of muscle activity in TRA by 30 – 50% and EDC by ~ 10%, which can have protective effect on work-related musculoskeletal disorders.
- During time pressured conditions, overall biofeedback lowered muscle activity in the contra lateral TRA and the EDC compared to control but not during the non-time pressured working condition.

CONCLUSION 2:

- *DYN* low-force contractions caused higher EMG and MMG activity than *IST* contractions. IMP was lower during *DYN* vs. *IST* low-force contraction, which may account for the reduction in TO₂ not being larger during *DYN* vs. *IST* contraction.
- *SST* low force contractions caused lower mean MMG activity than *DYN* and *IST* contractions. Mean reductions in TO₂ was larger during *SST* vs. *IST* and *DYN* low-force contractions, which may be due to higher mean IMP during *SST* vs. *IST* and *DYN* contractions.
- *SST* low-force contractions for 10 min induced acute fatigue development but TO₂ did not underlie the fatigue development despite a 4-fold increase in IMP.
- No single contraction mode meet the criteria of a low muscle activity as well as a low metabolic load in terms of low IMP and consequently optimal conditions for blood flow and the TO₂ to prevent muscle fatigue over time. Thus, the hypothesis of the existence of a single optimal contraction mode for preventing muscle fatigue and WRMD was rejected.

Conclusively, when formulating criteria and efficient intervention strategies for the prevention of work-related musculoskeletal disorders due to repetitive low-force work, biofeedback as well as a combination of various muscle contraction modes performed through different time and force exposure profiles is recommended.

Resumé (Dansk)

Introduktion

Forhøjet statisk muskelaktivitet er anerkendt som en af de væsentligste risikofaktorer for udvikling af arbejdsrelaterede muskelskeletalelidelser (WRMD). Derfor er det generelt accepteret i litteraturen at forebyggelse af muskelskeletalelidelser bedst sker under anvendelse af dynamisk- frem for statisk muskelkontraktion. På trods af denne konsensus i litteraturen findes der basale muskelfysiologiske resultater, der påpeger på at den totale energiomsætning i muskulaturen er større under dynamiske- frem for statiske kontraktioner under sammenlignelige kraftudviklingsprofiler. Der eksisterer altså modstridende hypoteser vedrørende kontraktionsrelaterede skader på bevægeapparatet.

Det overordnede formål med denne afhandling er at fastlægge mulige interventionsstrategier på arbejdspladsen, der kan forebygge udviklingen af WRMD under ensidigt lav-intensivt arbejde. De specifikke delmål for afhandlingen er: 1) ved hjælp af biofeedback at minimere unødigt muskelaktivitet under et standardiseret computerarbejde, der udføres under to forskellige arbejdsforhold (*Studium I*); 2) at bestemme det optimale muskel kontraktionsmønster under lav-intensivt arbejde på baggrund af minimal elektrisk, mekanisk og metabolisk respons (*Studium II og III*).

Metode

Studium I: Elleve forsøgspersoner udførte standardiseret computerarbejde under to forskellige arbejdsbetingelser (med og uden tidspres) med eller uden biofeedback. Visuelt eller audielt biofeedback blev givet via to forskellige muskler i overekstremiteten (*højre m. trapezius (TRA) eller højre m. extensor digitorum communis (EDC)*) på baggrund af elektromyografi (EMG) eller mekanomyografi (MMG) målinger. Effekten af tidspres og biofeedback blev vurderet via EMG fra højre og venstre TRA samt højre EDC.

Studium II: Otte forsøgspersoner udførte lav intensive, statiske og dynamiske muskelkontraktioner med identisk tids-kraft index som 1 min. albuefleksion udført med tre kontraktionstyper. Arbejdsprotokollerne bestod af, 1) en vedvarende statisk session (SST) ved 5 (LAV) og 10 (HØJ) %MVC; 2) en dynamisk session (DYN) bestående af en 20° albueledsbevægelse, opdelt i en 2 sek. koncentrisk fase og en 2 sek. ekcentrisk fase (gennemsnitlig bevægelseshastighed: 10°/sek), med en efterfølgende 4 sek. pause; og 3) en intermitterende statisk session (IST) med 4 sek. kontraktionsperiode

efterfulgt af en 4 sek. pause. DYN og IST resulterede i 8 kontraktioner pr. kontraktionstype og hver kontraktionstype blev gennemført ved 10 (LAV) og 20 (HØJ) %MVC.

Forsøgene blev vurderet via EMG, MMG, intramuskulært tryk (IMP), og ilttensionen (TO_2) i m. biceps brachii.

Studium III: Syv forsøgspersoner udførte en statisk albueledsfleksion ved 10 %MVC i 10 min. 5% MVC test kontraktioner blev gennemført før arbejdsprotokol samt efter 10 og 30 min efterfølgende restitution. Forsøgene blev vurderet via EMG, MMG, intramuskulært tryk (IMP), og ilttensionen (TO_2) i m. biceps brachii.

Hovedresultater

Studium I: EMG aktivitet i TRA var reduceret med henholdsvis ~ 30% og ~ 50% i højre og venstre side ved feedback fra højre TRA i forhold til kontrolsituationen (højre: 1.7 ± 1.2 vs. 2.4 ± 1.1 %max-EMGrms, $P = 0.07$; venstre: 1.2 ± 1.2 vs. 2.5 ± 2.1 %max-EMGrms, $P = 0.05$). EMG aktivitet i EDC var reduceret med ~ 10% ved feedback fra EDC i forhold til kontrolsituationen (8.3 ± 3.4 vs. 9.1 ± 3.1 %max-EMGrms, $P = 0.003$). Under tidspres var aktiviteten reduceret i højre TRA (1.9 ± 1.3 %max-EMGrms, $p=0.08$), venstre TRA (1.5 ± 1.5 %max-EMGrms, $p=0.09$), og EDC (8.4 ± 3.2 %max-EMGrms, $p=0.002$), ved generel feedback i forhold til kontrolsituationen.

Study II: EMGrms and MMGrms var højere i DYN end i IST (koncentrisk fase: DYN vs. IST var 14.2 vs. 9.4 and 22.0 vs. 15.9 %max-EMGrms; ekcentrisk fase: i DYN, MMG var ~1.5 og ~2.0 gang højere end IST ved hhv. 10 and 20 %MVC). IMP i den koncentriske fase i DYN var lavere end IST (2.3 vs. 29.5 and 10.9 vs. 42.0 mmHg ved hhv. 10 and 20 %MVC), med et lignende billede for den ekcentriske fase. Ingen forskel blev vist i reduktionen af TO_2 i hverken kontraktions- eller hvileperioderne. Gnm. MMGrms i SST var lavere end IST og DYN (LOW: 3.9 ± 0.9 vs. 5.8 ± 1.1 (IST) og 6.7 ± 1.4 (DYN) $\cdot 10^{-3} \cdot m \cdot s^{-2}$; og HIGH: 4.2 ± 0.9 vs. 7.0 ± 1.5 (IST) og 8.7 ± 1.8 (DYN) $\cdot 10^{-3} \cdot m \cdot s^{-2}$). Gnm. IMP i SST var højere end DYN (LOW: 16.8 ± 4.9 vs. 8.5 ± 3.9 mmHg; og HIGH: 25.4 ± 7.5 vs. 12.6 ± 4.9 mmHg), hvilket resulterede i en 2.0 gange store gnm. reduktion i TO_2 i SST end ved DYN og IST.

Study III: Under 10%MVC_{10min} steg MMGrms fra 0.04 ± 0.01 til 0.11 ± 0.07 $m \cdot s^{-2}$ i det sidste minut og MMGmpf og EMGmpf faldt hhv. fra 34.9 ± 8.2 til 21.3 ± 3.8 Hz samt fra 71.7 ± 10.9 til 61.7 ± 10.0 Hz. Initialt faldt TO_2 med $6.9 \pm 6.5\%$ fra hvileniveau men tilbagevendte til hvileniveau indenfor 1 min. IMP

forblev konstant under hele kontraktionen efter en initial stigning på 4 gange hvileniveau som var 12.2 ± 10.4 mmHg.

KONKLUSION 1:

- Biofeedback nedsatte muskelaktiviteten i TRA med 30 – 50% og i EDC med ~ 10%, som kan have en beskyttende effekt på udviklingen arbejdsrelaterede muskelskeletale lidelser.
- Under tidspres, reducerede biofeedback muskelaktiviteten i den kontra laterale TRA og EDC i forhold til kontrolsituationen men ikke under den ikke-tidspresset arbejdsbetingelse.

KONKLUSION 2:

- *DYN* lav intensive kontraktioner resulterede i højere EMG og MMG aktivitet end *IST* kontraktioner. *IMP* var lavere under *DYN* vs. *IST* lav intensive kontraktioner, hvilket kan have forårsaget at reduktionen i TO_2 ikke var større ved *DYN* vs. *IST* kontraktioner.
- *SST* lav intensive kontraktioner resulterede i lavere gnm. MMG aktivitet end *DYN* og *IST* kontraktioner. Gnm. reduktion i TO_2 var større under *SST* vs. *IST* og *DYN* lav intensive kontraktioner pga. højere gnm. *IMP* under *SST* vs. *IST* og *DYN* kontraktioner.
- *SST* lav intensive kontraktioner i 10 min forårsagede akut træthedsudvikling men TO_2 kunne ikke forklare udviklingen af træthed på trods af en 4 gange stigning i *IMP*.
- En enkelt muskelkontraktionstype kunne ikke opfylde kriteriet for lav muskel aktivitet samt lav metabolisk belastning i form af lav *IMP* og dermed optimale forhold for blodgennemstrømningen og ilttilførslen til musklen for at forebygge muskeltræthed over tid. Hypotesen vedr. eksistensen af en enkelt optimal muskelkontraktionstype for forebyggelsen af muskeltræthed og WRMD blev afvist.

Ved fastlæggelse af kriterier og effektive interventionsstrategier på arbejdspladsen, der kan forebygge udviklingen af WRMD under ensidigt lav-intensivt arbejde, anbefales biofeedback samt en kombination af varierende muskelkontraktionstype udført med forskellige tids- og kraftudviklingsprofiler.

List of abbreviations

BP	blood pressure
DYN	dynamic contraction
EDC	m. extensor digitorum communis
EMG	electromyography
IMP	intramuscular pressure
IST	intermittent static contraction
LFF	low frequency fatigue
MAP	mean arterial pressure
Mb	myoglobin
MMG	mechanomyography
mpf	mean power frequency
MVC	maximal voluntary contraction
MU	motor unit
NIRS	Near Infrared Spectroscopy
rms	root mean square
RPE	rating of perceived exertion
rTO ₂	reduction in muscle tissue oxygenation
SR	sarcoplasmic reticulum
SST	sustained static contraction
TO ₂	muscle tissue oxygenation
TRA	m. trapezius, upper
WRMD	work-related musculoskeletal disorders

1. Introduction

An increasing effort to investigate the causes of musculoskeletal disorders and to implement intervention to prevent disorders has been put forth the last decades. This has resulted in recognition from workers as well as employers that a relationship exist between multiple exposures within working environment and the development of work-related musculoskeletal disorders (WRMD). However, it is still thoroughly debated how significant work-related and individual psychosocial factors are compared to work-related physical and mechanical exposures in the development of musculoskeletal disorders (Kryger *et al.*, 2003;Bonde *et al.*, 2005). Musculoskeletal disorders have a high socio-economic cost in the means of lost working days due to illness, increased health expenses, and early retirements and therefore comprise a significant problem in modern society. During the last decades, musculoskeletal disorders have been the most common reported work-related problem in Denmark (Westgaard & Winkel, 1997;Arbejdstilsynet, 2001). The Danish Confederation of Trade Unions recently reported the socio-economic cost due to musculoskeletal disorders to be up to 7.3 billion Dkr in 2005. In the UK, 4.1 million working days were lost in 2001/02 due to WRMD in the upper extremities that were caused or worsened by work (for reference see (Buckle, 2005)). The highest prevalence of musculoskeletal disorders is often seen in the upper extremities in subjects working with repetitive low-force work (Kilbom, 1994;Ohlsson *et al.*, 1995;Punnett & Bergqvist, 1997;Punnett & Bergqvist, 1999;Jensen *et al.*, 2002). Repetitive low-force work has been observed during a number of occupations today, e.g. intensive man machine interfacing as when working with computer input devices, and related to disorders in the arm and shoulder/neck region (Hägg, 2000). The use of computer has increased dramatically. In Denmark, 60% of the Danish workforce used a computer at work and 19% used the computer more than 75% of the work time (Burr, 2000), which are conditions that are assumed to increase in the coming years. WRMD is defined as a multi-factorial phenomenon that includes work exposure as a significant contributor to the development of musculoskeletal disorders (WHO, 1985), and is believed to have a multi-factorial etiology. The *etiologic fraction of occupational health* was 10-21% for musculoskeletal disorders diagnosed at hospitals in 1994-99. This denotes that work-related risk factors accounted for 10-21% of musculoskeletal disorders (Bach *et al.*, 2002) and suggests a potential of an occupational intervention program. Epidemiologic studies may have identified gross risk factors. Yet mechanistic research studies are needed in combination with the epidemiologic studies to specify intervention strategies that should subsequently be tested in large scale epidemiologic

studies. Clarification of the muscular response, in terms of the muscle activity and metabolism, due to different mechanical exposure profiles is a prerequisite when formulating criteria and efficient strategies for the prevention, treatment, and rehabilitation of musculoskeletal disorders.

1.2. Risk factors for developing work-related musculoskeletal disorder

A number of major risk factors for developing WRMD have been proposed in the literature. Factors such as prolonged low-level static muscle activity, highly repetitive contractions and movements, duration of contraction time, insufficient muscular rest and recovery periods, awkward and static postures, work composition, and psychosocial factors in terms of mental stress are suggested to influence the development of WRMD (Hägg, 1991; Bongers *et al.*, 1993; Kilbom *et al.*, 1996; Malchaire *et al.*, 2001; National Research Council and the Institute of medicine, 2001; Devereux *et al.*, 2002; Blatter & Bongers, 2002; Visser & van Dieen, 2006). Exposure to such risk factors triggers a number of physiological responses that may have a deteriorating impact on the muscular function. Prolonged impairment of the muscular function can lead to muscle dysfunction and subsequently muscle disorders. Thus, in the following are discussed different risk factors and their mechanisms that may influence the development of WRMD.

1.2.1. Muscle fatigue

Muscle fatigue may be considered as a major risk factor for developing WRMD as it is a physiological consequence of prolonged sustained or repeated muscle contractions and insufficient recovery. Muscle tissue is capable of generating active force, work, and power. During sustained or repeated contractions, the muscles exhaust and fail to maintain the required force, work, or power. Numerous muscle fatigue studies have analyzed static muscle contraction, which is defined as a contraction where the muscle develops force at constant length. The dependent variable often used as a fatigue marker is the force development, and muscle fatigue has therefore been defined as the progressive loss of force generating capacity or decline in maximal force development with repeated muscle contractions over time (Gibson & Edwards, 1985; Vøllestad *et al.*, 1988; Ameredes & Clanton, 1990; Lannergren & Westerblad, 1991). Muscle fatigue has in addition been defined as a failure to maintain the required force or intensity, which also is the definition of exhaustion (Edwards, 1983). However, human movement is primarily based on mechanical performance where movement is created by skeletal

muscles that shorten. As the muscular load is dependent on contraction speed (De Ruyter *et al.*, 1998), the force-velocity relationship is an important physiological aspect to consider when evaluating the low-level exertion in the workplace. During dynamic activity, the dimensions length, force, and time, must be taken into account, if compound variables such as shortening velocity, work, and power are to be quantified. Therefore, muscle fatigue is also defined as a decline in the capacity to shorten, perform work, and produce power (Edwards, 1983). Thus, sustained or repetitive muscle contractions, regardless of the muscle contracting statically or dynamically, for a prolonged period of time facilitate muscle fatigue leading to an impairment of muscle function. Adequate time for recovery may then be essential in the prevention muscle dysfunction and the development of muscle disorders.

Low frequency fatigue (LFF) has been identified as *a form of muscle fatigue that is characterized by reduced tetanic tension at low frequencies of stimulation while tetanic tension at high stimulus frequencies is close to normal* (Westerblad *et al.*, 1993). LFF is also characterized as long-lasting fatigue and the recovery being very slow (Edwards *et al.*, 1977; Jones, 1996), which has been acknowledged as a result of impaired excitation-contraction coupling (Ørtenblad *et al.*, 2000; Hill *et al.*, 2001). As LFF additionally is associated with a reduced sarcoplasmic reticulum (SR) Ca^{2+} release (Westerblad *et al.*, 1993), LFF may be a cause of altered calcium homeostasis, which also may play a significant role in morphological changes and muscle tissue damage (Jackson *et al.*, 1984; Favero, 1999; Berchtold *et al.*, 2000). The intracellular free Ca^{2+} concentration is proposed to be an essential regulator of many cell processes including oxidative status and metabolism and is the primary activator of many enzymes that are important for maintaining the structural integrity of the cells (Berchtold *et al.*, 2000). Low-force contractions have been shown to cause LFF as the rate of the force generating capacity was hampered (Bystrom & Kilbom, 1991; Blangsted *et al.*, 2005). LFF has also been demonstrated in the forearm muscle during computer mouse work (for reference see (Westerblad *et al.*, 2000)). LFF obtained in successive work periods is additive, which indicates full recovery from the first work bout is essential, before the next work bout is initiated (Chin *et al.*, 1997). Thus, the recovery period is dependent on the type of work that resulted in muscle fatigue in the means of exposure time (Jones, 1996). The required recovery following fatigue induced by short termed high-force exertions is short termed, where as the adequate recovery following prolonged low-level muscle activity is slower. If LFF arises in the low threshold MU, sufficient recovery is required if intervention of muscle fatigue and tissue damage is the intention.

1.2.2. *The Cinderella Hypothesis*

The skeletal muscle *per se* may not be fatigued or exhausted due to low-level muscle activity, but it may be the case for the single muscle fibers. The alpha motor neuron, its axon, and the muscle fibers it innervates comprise the motor unit (MU) (Rhoades & Tanner, 1995). The alpha motor neurons are divided into two subpopulations according to their size. The large neurons are rapidly conducting, have high threshold to synaptic stimulation and innervate fast twitch muscle fibers. The small motor neurons are slowly conducting, have low threshold to synaptic stimulation, and innervate slow twitch muscle fibers. The Henneman's size principle comprises the suggestion of a fixed MU recruitment and de-recruitment pattern during repeated muscle activation pattern (Henneman, 1957) starting with the low threshold MU (type 1) when synaptic activity is low, producing low-force contractions. Thus, the low threshold MU remain active until total relaxation of the muscle occurs; also known as *the Cinderella hypothesis* (Hägg, 1991). The Cinderella hypothesis provides a feasible explanation for the muscle damage of the continuously activated MU and development of WRMD of the low threshold MU. When working with prolonged and low-force loads as in repetitive monotonous work, some MU will become fatigued and overloaded mechanically and metabolically in spite of the muscle as a whole is working at a low energy demand (Hägg, 1991;Kadefors *et al.*, 1999). Cinderella fibers have been identified during repetitive low-force muscle activity, during both static and dynamic muscle contractions with increasing force development (Sjøgaard, 1995;Sjøgaard *et al.*, 1996;Sjøgaard & Sjøgaard, 1998;Kadefors *et al.*, 1999;Forsman *et al.*, 1999;Westgaard & De Luca, 1999;Thorn *et al.*, 2002;Zennaro *et al.*, 2003). Myalgia may arise because of such low-force muscle activity and a stereotyped motor unit recruitment pattern, which has been hypothesized to result in muscle damage (Sjøgaard *et al.*, 2000;Hägg, 2000). As a stereotyped work and task pattern may elicit a stereotyped recruitment pattern of the MU, the prevention would then be task variations to break such recruitment pattern. Avoidance of fatigue or reduction of especially unnecessary activity of single muscle fibers through work variation and sufficient recovery is therefore inevitable for effective prevention of WRMD.

1.2.3. *Intramuscular pressure and muscle tissue oxygenation*

Degenerating changes in muscles from persons suffering from work-related myalgia have been seen in biopsies from m. trapezius and m. extensor carpi radialis as moth eaten and ragged red fibers (Hägg, 2000). These fibers have been characterized as a morphological sign of disturbed mitochondrial

metabolism that often occurs in slow twitch (ST) fibers, which are activated at low force levels (Larsson *et al.*, 1988). When skeletal muscle is exposed to sustained or highly repeated muscle contraction regardless of contraction mode, a sufficient muscle blood flow to the contracting muscle is essential to maintain muscle homeostasis, which is challenged by an increased energy turnover and metabolite accumulation (Sadamoto *et al.*, 1983b; Rosendal *et al.*, 2004a; Rosendal *et al.*, 2004b). Local circulatory hindrance consequently disturbs the muscle homeostasis (Edwards, 1988; Jonsson, 1988; Sjøgaard & Sjøgaard, 1998; Kadefors *et al.*, 1999; Sjøgaard *et al.*, 2000). Hampering of blood flow and reduction in muscle tissue oxygenation during sustained repetitive work has been suggested to contribute to the development of WRMD (Carayon *et al.*, 1999; Van Galen *et al.*, 2002). An increased intramuscular pressure is suggested to impede microcirculation by compression of the vascular beds and a well supported explanation for the lack of blood supply (Jarvholm *et al.*, 1988; Jensen *et al.*, 1995a). The microcirculation is completely blocked when IMP exceeds blood pressure. The intramuscular pressure is related to force production, the shape, and location of the muscle with high pressure at high forces, in cylindrical and deep muscles (Sejersted *et al.*, 1984). During static contractions intramuscular pressure (IMP) has been shown to increase with contraction force and has been associated with impairment of blood flow and hence contribute to muscle fatigue (Sejersted & Hargens, 1995; Jensen *et al.*, 1999a; Sjøgaard *et al.*, 2003). A causal relationship between muscle performance and ischemia has been demonstrated during high-force contractions (Hogan *et al.*, 1994). During sustained low-force contractions, the continuous activity in the subset of active MU may cause a local energy crisis, due to a localized increase in IMP in the surrounding fibers. It is at present still uncertain if insufficient oxygen supply underlies fatigue development induced by low-level contractions (Sjøgaard *et al.*, 1986; Røe & Knardahl, 2002). Low-force static contractions at 5% MVC (Murthy *et al.*, 1997; Jensen *et al.*, 1999a) as well as computer mouse work (Heiden *et al.*, 2005) have, however, shown to cause a decrease in local tissue oxygenation. Discrepancy in the conclusions regarding sufficient muscle tissue oxygenation during low-force contractions can be due to methodical differences between the studies. Evidence of obstruction of blood flow due to IMP yet below blood pressure has been demonstrated in studies investigating tissue oxygenation and hyperaemia following exercise (Bystrom & Kilbom, 1990; Jensen *et al.*, 1993a; Murthy *et al.*, 1997; Røe & Knardahl, 2002). Hyperaemia was also documented following isometric contractions at only 2.5% MVC (Jensen *et al.*, 1993a) and computer work (Røe & Knardahl, 2002). IMP levels of 30 mmHg for a

prolonged period of time (8 h) has shown to cause muscle fiber damage at normal blood pressure (Hargens *et al.*, 1981). In support of this notion, biopsy studies on myalgia patients demonstrated an impaired local blood flow and a depression of oxygen availability to be associated with structural abnormalities in the muscle fibers (Larsson *et al.*, 1988;Larsson *et al.*, 1990;Larsson *et al.*, 1999).

1.3. Intervention strategies

The described risk factors and possible underlying mechanisms, which all are suggested to play major roles in the development of WRMD, cannot fully explain the pathophysiology or etiology of the development of WRMD and thereby point out an evident and potential intervention strategy. However, some factors may be possible to affect. Sustained low-force muscle activity is likely to coincide with selective and stereotyped activation of low threshold MU as proposed in the Cinderella hypothesis leading to muscle fatigue at cellular level. Fatigue may lead to calcium accumulation in the active motor units and other homeostatic disturbances due to limitations in local blood supply and metabolite removal in muscle compartments with larger numbers of active MU. Such exposure for a prolonged period of time can lead to muscle disorders. The key-factor in this scenario is the duration of continuous and stereotyped muscle activity and intervention should therefore target the time factor of activity and work patterns.

1.3.1. Biofeedback

In view of the *Cinderella hypothesis* and the mechanisms that may underlie muscle fatigue, subjects suffering from myalgia and WRMD may benefit from electromyography (EMG) biofeedback, which may contribute to an awareness of a sustained muscle activation pattern that may result in a reduction of muscle activation. Such a reduction of muscle activity not being of necessity for a given task and conceivably an interruption of the sustained muscle activity can be the result of biofeedback. EMG biofeedback has earlier been used to reduce EMG muscle activity in both m. trapezius and forearm muscles (Poppen *et al.*, 1988;Palmerud *et al.*, 1995;Gerard *et al.*, 2002;Hermens & Hutten, 2002). Finger flexor EMG biofeedback and typing force feedback presented to touch typists, reduced the 90th percentile typing force, finger flexor, and extensor EMG by 10-20% (Gerard *et al.*, 2002). EMG biofeedback from the upper trapezius resulted in a 7-12% reduction in the EMG amplitude in both right and left trapezius during standardized typing tasks in subjects with computer-work related myalgia

(Hermens & Hutten, 2002). Thus, it seems that biofeedback may have a beneficial effect on reducing EMG muscle activity. However, before recommending biofeedback as a preventive strategy a number of aspects should be elucidated. The involved muscles during computer work, which are evaluated in *study I*, work differently regarding the contraction mode. The trapezius muscle acts as a shoulder stabilizer and contracts primarily statically, whereas m. extensor digitorum communis contracts dynamically by being the prime mover during computer work. Due to differences in the contraction mode, TRA and EDC may also respond distinctively in the muscle activation pattern when introduced to biofeedback.

Recently, a systematic literature search reviewed the effect of augmented feedback on motor function of the upper extremities (van Dijk *et al.*, 2005). Different therapeutic interventions using feedback, such as EMG biofeedback, kinetic or kinematic feedback, showed no difference in effectiveness of improving motor function. It may then be speculated that the exposed time pressure and stress it may cause, which are common risk factors during computer work (Punnett & Bergqvist, 1997), impedes the effectiveness of the biofeedback. Therefore, it is pertinent to test the working condition under which biofeedback is implemented together with a subjective evaluation of the usefulness of the biofeedback. Mental demands have been associated with increased muscle activity (Jensen *et al.*, 1998). Psychological stress and cognitive demands can elicit non-postural muscle activity (Lundberg *et al.*, 1994), which may contribute to an over-activity of single MU. During standardized finger movements and mouse clicking, motor unit (MU) activity in EDC was shown in spite of no physical requirement (Søgaard *et al.*, 2001). MU activity was detected both before and after ended double click and even during contra lateral finger moving suggesting a continuous activation of specific MU throughout computer work. Increased muscle activity above rest in the non-keying contra lateral trapezius has been demonstrated during keying tasks (Blangsted *et al.*, 2004). Therefore, whether biofeedback can reduce the excessive muscle activity in the contra lateral trapezius muscle during computer mouse work to prevent muscle fatigue is a significant aspect to be addressed.

1.3.2. Work composition

The exposure time of the muscle activation seems essential to limit as the time factor plays a significant role in the development of muscle fatigue and the following recovery. Therefore, an important dimension in the prevention of muscle fatigue development is the work/rest pattern in repetitive

monotonous work (Christensen *et al.*, 2000). A work/rest pattern can be composed in various combinations by varying the mean force load, cycle time, and duty cycle (Mathiassen, 1993). Mean force load comprise the averaged force load during a given work period – also known as the time-tension product, cycle time comprise the sum of the contraction and rest time period, and finally duty cycle comprise the contraction period relative to the cycle time. By varying these components an intermittent work protocol can be assembled, which then is in contrast to the characteristics of a sustained work protocol, where no rest is engaged. A cycle time of < 30 s or same movements performed 50% of cycle time has been suggested as the limit of repetitive work to identify workers in high risk of developing musculoskeletal disorders (Silverstein *et al.*, 1986). A reduction in the shoulder-neck exposure was demonstrated when reducing the work pace (Mathiassen & Winkel, 1996). In relation to the etiology of muscle fatigue, a sufficient recovery period is indispensable for the muscle to perform subsequently with its full functional capacity. As the length of recovery is dependent on the exposure time, duration of work and the rest are to be matched to the intensity and mode of contraction in the working period (Mathiassen, 1993; Sjøgaard & Jensen, 2006). However, the effect of different intermittent work compositions on fatigue development and recovery may at first seem beneficial, as pause intervention has shown to increase endurance time and lower the perceived exertion compared to sustained exercise, but the metabolic response and muscle activity during intermittent vs. sustained exercise did not differ (Bystrom *et al.*, 1991). However, a more pronounced response of EMG and a decline in MVC was demonstrated following intermittent vs. sustained exercise indicating the recovery to depend upon cycle time and duty cycle (Mathiassen, 1993). Likewise, it has been demonstrated that intermittent exercise can result in larger disturbances in the metabolic homeostasis than sustained exercise of equal duration and work load (Sjøgaard, 1990). However, recovery of MVC was slower after sustained vs. intermittent exercise at 25% MVC (Bystrom *et al.*, 1991). The need for a prolonged recovery period may be a sign of LFF. Therefore, variations in the work pace and the work/rest pattern may show different activation patterns in fatigued muscle and thereby prevent fatigue as well as LFF. Yet it is still to be clarified how cycle time and duty cycle performed through different contraction modes affect the muscular response before recommending a more specified cycle time and duty cycle as a preventive strategy. It is commonly recognized that more mechanical exposure variation would be an effective intervention of developing WRMD (Kilbom, 1994; Konz, 1998; National Research Council and the Institute of medicine, 2001). To elicit mechanical exposure variations, the mode of muscle

contraction; i.e. static and dynamic muscle contractions, may be another important aspect to consider when formulating the essential work composition, as the metabolic requirement and the physiological response have shown to depend on the performed work task.

1.3.3. Muscle contraction modes

As mentioned, static muscle activity has been identified as one of the major risk factors in the development of WRMD (Kilbom & Persson, 1987; Bernard, 1997; Punnett & Bergqvist, 1997; Sjøgaard & Jensen, 2006). In line with the above studies on work composition, low frequency fatigue was demonstrated to persist for a longer period of time (24 h) after sustained vs. intermittent static contractions of 15% MVC (Bystrom & Kilbom, 1991) suggesting a more pronounced fatigue response following sustained vs. intermittent static contractions (Bystrom *et al.*, 1991; Mathiassen, 1993). However, intermittent static contractions at low force levels have also shown to induce long-term fatigue, which was evident even after 30 min of recovery as quantified from EMG and mechanomyography (MMG) (Sjøgaard *et al.*, 2003). Therefore, static contractions have been abandoned in general in the occupational setting and has lead to suggesting that dynamic contractions are preferable to static contractions in the prevention of WRMD (Takala, 2002). Conversely, according to basic muscle physiological findings, the total metabolic energy consumption rate and decrease in energy stores have been shown to be larger when a given force is developed during dynamic compared to static contractions (Bridges *et al.*, 1991). The pioneer study of Fenn (1923), demonstrated that heat was liberated from a contracting muscle. A proportional relationship exists between the heat liberation and the work, which the muscles perform when shortening ('Fenn effect') (Fenn, 1923). A muscle performing work liberates an extra amount of heat, which does not appear in a static contraction at corresponding force development. When assuming heat liberation to be proportional to energy consumption, it is believed that more energy is consumed in a muscle performing work (dynamic) compared to a muscle performing only tension (static) but no work. The results of Fenn have later been confirmed by showing an additional energy metabolism and a larger decrease in energy stores in muscles contracting dynamically compared to statically (Hill, 1938; Bridges *et al.*, 1991). Energy calculations suggest that crossbridge lifetime is less when shortening occurs compared with static contractions (Woledge *et al.*, 1985). Therefore, it may be presumed that energy consumption is larger during muscle shortening. For identical, electrical stimulation patterns, a lower force was developed for

dynamic contractions than for static contractions and a corresponding lower Pi/PCr ratio (Bridges *et al.*, 1991). Their results also imply that the Pi/PCr ratio is larger when a given force is performed during dynamic compared with static contractions. Since the Pi/PCr ratio is proportional to the rate of ATP consumption, the study indicates that the amount of total energy consumption is larger for a given force if this force is exerted through a distance. Some studies have reported a difference in the development of fatigue induced by repeated static and dynamic muscle contractions (Seow & Stephens, 1988; Cummins *et al.*, 1989; Ameredes & Clanton, 1990; Ameredes *et al.*, 1992; Vedsted *et al.*, 2003). These studies demonstrated that the loss of force development was significantly larger after repeated dynamic contractions than after intermittent static contractions, which demonstrates that the degree of fatigue induced by muscle shortening is significantly higher than fatigue elicited by static contractions and that fatigue development is dependent on the contraction mode.

Noteworthy, is that both during intermittent static and dynamic contractions, the cycle time and duty cycle are essential for the conditions for the muscle homeostasis. As a repeating duty cycle is an element in the dynamic and intermittent static working modes, the muscle pump activity creates optimal conditions for the blood flow. Investigation of the blood flow following concentric muscular activity or passive venous compression showed that concentric contractions produced higher blood flow than passive venous compression (Zhang *et al.*, 2004). The mechanism was explained in terms of the rhythmic muscle contraction repeatedly emptying the veins and facilitating perfusion of the skeletal muscle. Such a condition is not present during a sustained static muscle contraction, which may aggravate the muscle function even during low-force contractions. The reduction in muscle tissue oxygenation during sustained static contractions may therefore be larger than that of intermittent static contractions. IMP has shown to be larger during dynamic than static contractions (Sjøgaard *et al.*, 2004) and increase with the shortening velocity of the dynamic contractions (Degens *et al.*, 1998) suggesting a larger obstruction of the oxygen delivery to the muscle. It may then be speculated that also the reduction in muscle tissue oxygenation is larger in dynamic compared to intermittent static contraction in spite of a relaxation period in both contraction modes. Voluntary contractions at identical time-tension product resulted in no difference in cardiovascular pressure response to dynamic and static contractions at comparable workloads, i.e. same peak tension and time-tension product (Stebbins *et al.*, 2002). Therefore, a larger reduction in muscle tissue oxygenation with dynamic contraction may be further exacerbated in the light of the different fatigue responses after dynamic and static contractions

reported in aforementioned *in vitro* studies. Thus, the additional external work performed by shortening muscles may lead to larger energy turnover and energy depletion. Therefore, in spite of identical time-tension product, cycle time, and duty cycle, dynamic contractions are still believed to be less beneficial due to higher energy consumption than that of intermittent static contractions. However, the increase in the energy cost of a contraction with shortening is dependent upon the initial muscle length (Stainsby, 1982). Hence, to demonstrate valid evidence of differences in fatigue development between static and dynamic contractions further investigation of the muscular response during different contraction modes is needed, as many mechanical factors are to be controlled and/or kept constant.

2. Aim and hypotheses

The overall aim of the present thesis is to identify possible intervention strategies in the workplace that may prevent the development of WRMD due to repetitive low-force work. The muscular response during computer work and standardized muscle contractions, comparable to occupational exposures, was determined. The specific aims were:

AIM 1:

To minimize unnecessary muscle activity through biofeedback during standardized computer work under various working conditions (*Paper I*).

The working hypotheses were:

- Unilateral biofeedback from upper m. trapezius (TRA) can reduce bilateral TRA activity but not activity in more remote muscle, i.e. m. extensor digitorum communis (EDC)
- Biofeedback from EDC can reduce activity in EDC but not in TRA
- Biofeedback is more effective in the *non-time pressured* than in the *time pressured* working condition.

AIM 2:

To determine the optimal muscle activation mode when performing low-force activities based on minimal electrical, mechanical, and metabolic response (*Paper II and III*).

The working hypotheses were:

- *Dynamic* compared with *intermittent static* low force contractions performed with identical duty cycle and time-tension product cause
 - higher EMG and MMG amplitude
 - higher intramuscular pressure
 - larger decrease in muscle tissue oxygenation

- *Sustained* compared with *intermittent* static low force contractions performed with identical time-tension product cause
 - higher mean EMG and MMG amplitude
 - higher mean intramuscular pressure
 - larger decrease in muscle tissue oxygenation

- *Sustained static* low force contractions cause muscle fatigue due to reduced muscle tissue oxygenation

3. Materials and methods

3.1. Subjects

All participating subjects were healthy and with no history of neuromuscular disorders and were all a part of the Danish work force. Informed consents were obtained from all participants and the studies were approved by the local ethical committee and conducted in conformity with the Declaration of Helsinki. All subjects were right-handed. All subjects were females except one in *study II*. The characteristics of the subjects are summarized in Table 1.

Table 1 – Data of participating subjects. Mean values (range)

	Study		
	I	II	III
No. of subjects	11	8	7
Age (years)	40 (26-56)	54 (45-69)	56 (45-69)
Height (cm)	168 (152-178)	163 (152-172)	162 (152-172)
Body mass (kg)	66 (51-83)	65 (60-73)	65 (60-73)

3.2. Experimental set-up

In *study I*, the subjects were seated at a standardized and adjustable computer work station in an upright position with flexed elbows and pronated forearms resting horizontally in the sagittal plane. Elbows and forearms were supported throughout the experiment. The table and chair were adjusted to accommodate each subject and ensure the most comfortable position as possible. At this work station, the subjects performed standardized computer work while receiving biofeedback.

In *study II* and *III*, the subjects were seated in an adjustable chair with their back and upper arms vertical and the forearms semipronated in the sagittal plane resting on a horizontal armrest, resulting in a 90 degrees elbow flexion (Fig. 1). In this position, the subjects performed either sustained or intermittent static, or dynamic elbow flexion with their left arm against a strap around the wrist. The strap was connected to a strain gauge transducer that was attached to either a weight or the floor depending on the contraction mode.



Figure 1 – Experimental set-up in *study II* and *III*.

To help the subject maintain the required force or angular elbow movement, visual force or position feedback was given, respectively. The feedback was shown on a computer screen in front of the subject.

3.3. *Experimental protocols*

3.3.1. *Study I*

To test the effect of biofeedback from upper limb muscles to reduce muscle activity, the subjects performed standardized computer (Fig. 2) work for 3 min during two different working conditions with time constraint and no time constraint induced by time pressure (*time pressure/no time pressure*) while receiving biofeedback. The biofeedback was given from two different muscles (*right TRA or right EDC*) through two different modes (*visual or auditory*) by the use of *EMG* as the biofeedback source. The design of the present study was a full 2^3 factors design. In total, each subject completed 14 different biofeedback sessions in a randomized order, as 6 additional biofeedback sessions with *MMG* as biofeedback source were performed. Prior to, halfway through, and after the biofeedback sessions, control sessions with *time pressure/no time pressure* were performed. During the control sessions, the tasks were identical to the work sessions but no biofeedback was given.



Figure 2 – *Experimental set-up in study I.*

When working with *time pressure*, the task was to complete each graph within 10 s, whereas during *no time pressure* there was no time limit for finalizing each graph. During *time pressure*, the subjects were occasionally unable to complete all graphs within the designated 10 s resulting in a lower number of graphs being completed than the number of graphs being initiated. The subjects were instructed to complete as many graphs and make as few errors as possible within the three minutes.

Three maximal voluntary contractions (MVC) for both TRA and EDC were recorded prior to the computer sessions.

The standardized computer work was performed by duplicating various graphs that were shown in the upper right corner of the computer screen (pixel resolution: 0.3 mm, screen resolution: 1024 x 768 pixels) (Birch *et al.*, 2000). The graphs were completed by clicking with the mouse cursor in a specific order on 6 circular targets (target point: 10 mm) displayed on the main part of the computer screen. A straight line was automatically drawn between two consecutively activated targets. A new graph came up when the former graph was completed. Number of completed graphs and mouse clicks were registered.

3.3.2. Study II

To evaluate the muscular response during static and dynamic low-force contractions with identical time-tension products, the subjects performed elbow flexion for 1 min in 3 working modes (Fig. 3). The working sessions were; 1) a sustained static session (SST) with a 1 min sustained static contraction at 5 (LOW) and 10 (HIGH) %MVC, 2) a dynamic session (DYN) as a 20° elbow movement with 2 s concentric phase, 2 s eccentric phase (mean movement velocity: 10 degrees/s), and 4 s resting period following each contraction, and 3) an intermittent static session (IST) with 4 s contraction period followed by a 4 s resting period. The DYN and IST session resulted in eight contractions for each working mode, and each session type was performed at two force levels: 10 (LOW) and 20 (HIGH) %MVC. Thus, the duty cycle was 50 % for DYN and IST with a cycle time of 8 s. After the last contraction in each session, recovery was followed for additionally 4 s giving a prolonged resting period of 8 s. The DYN session additionally included a session performed at 0 %MVC. To minimize any effect of a previous activity on the subsequent exercise bout, the lowest loads were always performed before the highest load, and the two static sessions before the dynamic session. A minimum of 5-10 min rest was allowed between sessions. Three MVCs were recorded prior to the designated protocol.

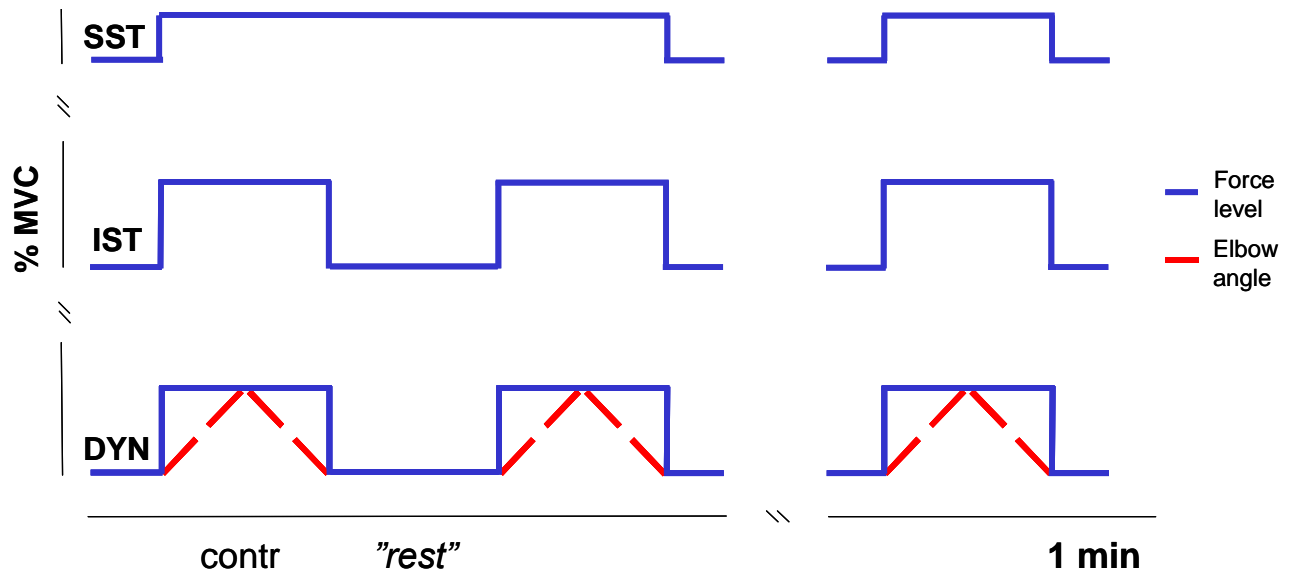


Figure 3 – Illustration of the dynamic (DYN) and intermittent static (IST) work sessions performed at 10 %MVC and 20 %MVC, and sustained static (SST) work session performed at 5 %MVC and 10 %MVC (study II). *contr*, contraction period. *rest*, resting period in DYN and IST.

3.3.3. Study III

To study the muscular response of muscle fatigue, the subjects performed sustained static elbow flexion at 10% MVC for 10 min (10%MVC_{10min}) (Fig. 4). Test contractions of 5% MVC were performed before (PRE), and after 10 min (R10), and 30 min (R30) of recovery. The force level during the test contractions was held constant for 1 min with the aid of visual feedback. Three MVCs were recorded prior to the designated protocol.

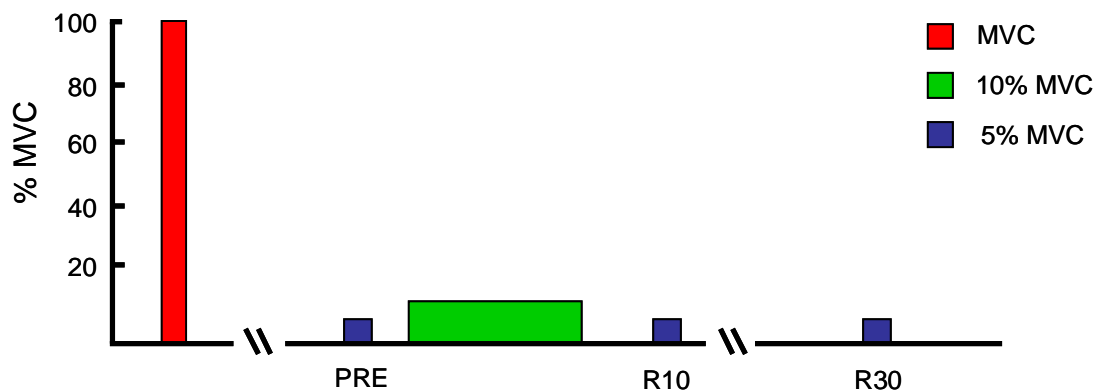


Figure 4 – Illustration of the experimental protocol in study III. 5% MVC test contractions were performed prior to the fatiguing sustained static elbow flexion at 10% MVC for 10 min and in the following recovery period of 30 min. MVC, maximal voluntary contraction. *PRE*, 1 min prior to fatiguing protocol. *R10*, 10 min recovery. *R30*, 30 min recovery.

Study II and *III* were carried out on two experimental days with identical protocol due to technical limitation of measuring TO_2 and IMP simultaneously. Force, EMG, and TO_2 were measured on one experimental day, which was the first day for 5 (*study II*) and 3 (*study III*) of the subjects. Force, EMG, MMG, IMP, and BP were measured on the other experimental day, which was the first experimental day for 3 of the subjects. In *study III*, one subject only performed one experimental day with measurements of force, EMG, MMG, TO_2 , and BP. Delay between experimental days was up to 22 days. The subjects in *study III* all participated in *study II*.

3.4. Methods

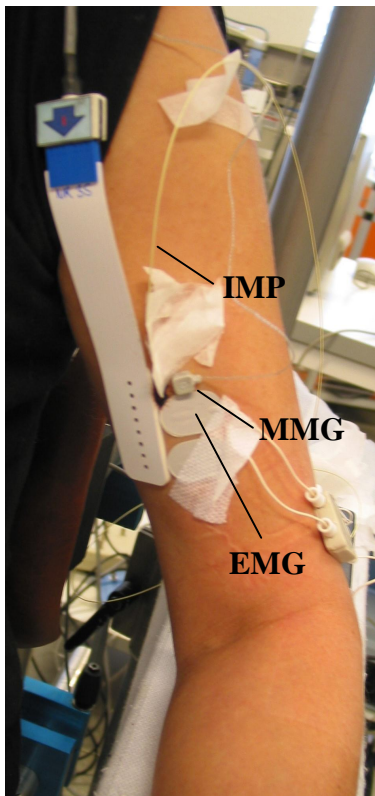
The methods and experimental protocols used in the 3 studies are summarized in Table 2.

Table 2 – Overview of used methods and experimental protocols

	Study		
	I	II	III
Experimental protocol			
Dynamic contractions; 0%, 10%, 20% MVC (4 s on/4 s off, 1 min)		X	
Intermittent static contractions; 10%, 20% MVC (4 s on/4 s off, 1 min)		X	
Sustained static contractions; 5%, 10% MVC (1 min)		X	
Sustained static contraction; 10% MVC (10 min)			X
Standardized computer work; (17 sessions x 3 min)	X		
Electromyography, EMG	X	X	X
<i>m. trapezius (TRA); upper right and left TRA</i>	X		
<i>m. extensor digitorum communis (EDC)</i>	X		
<i>m. biceps brachii</i>		X	X
Analysis of EMG			
Root mean square (EMGrms)	X	X	X
Mean power frequency (EMGmpf)			X
Mechanomyography, MMG		X	X
<i>m. biceps brachii</i>		X	X
Analysis of MMG			
Root mean square (MMGrms)		X	X
Mean power frequency (MMGmpf)			X
Tissue oxygenation, TO ₂		X	X
Intramuscular pressure, IMP		X	X
Analysis of TO ₂ and IMP			
<i>mean value</i>		X	X
<i>peak value</i>		X	
<i>nadir value</i>		X	
Blood pressure		X	X
Force	X	X	X
Goniometer		X	
Maximal Voluntary Contraction (MVC)	X	X	X
5% MVC test contractions; <i>sustained static contraction (1 min)</i>			X
Biofeedback	X		
Rate of Percieved Exertion (RPE); (0-9)	X		X
Subjective evaluation; <i>4-point scale</i>	X		

3.4.1. Electromyography

EMG was recorded by bipolar surface electrodes (Ag-AgCl electrodes, Neuroline 72501-K, Medicotest A/S, Ølstykke, Denmark). In *study I*, the electrodes were placed on both upper right and left TRA and



right EDC. For the upper right TRA, the electrodes were placed on each side of the MMG accelerometer (30 mm apart). For the upper left TRA, the electrodes were placed parallel and identically to the placement of the electrodes on the right TRA. For EDC, the electrodes were placed on each side of the MMG accelerometer (30 mm apart). Before mounting the electrodes, the skin was rubbed and cleaned with ethanol and then the impedance was checked to be below 12 kOhm. The EMG signal was amplified, low-pass filtered, and sampled with a sampling frequency of 2500 Hz or 1 kHz. In *study II* and *III*, the electrodes were placed on the belly of the m. biceps brachii without covering the end plate zone or getting too close to the musculotendinous region (Hermens & Freriks, 1997) (Fig. 5). The inter-electrode distance was 20 mm in order to fit the NIRS probe in between the EMG electrodes. For further description of the technical details for the analysis of the EMG signal, see the method section of the individual papers.

Figure 5 – Placement of bipolar surface EMG electrodes, the MMG accelerometer, and the intramuscular transducer-tipped pressure catheter on m. biceps brachii in *study II* and *III*.

3.4.2. Mechanomyography

To use MMG from the right TRA and EDC as a biofeedback source in *study I*, MMG was recorded by a piezoelectric accelerometer (Bang & Olufsen Technology, Struer, Denmark). On TRA, the accelerometer was attached to the skin with double sided adhesive tape and placed approximately 20 mm laterally from the mid distance between cervical vertebra C7 and acromion (Jensen *et al.*, 1993b). On the EDC, the accelerometer was placed one third of the distance between the lateral epicondyle and the radial styliod process (Delagi *et al.*, 1981). In *study II* and *III*, MMG was recorded from the m. biceps brachii by a 2-axis accelerometer (Analog ADXL202JE, Analog Devices, One Technology Way, P.O. Box 9106, Norwood, MA, USA). The accelerometer was placed on the m. biceps brachii proximal to the EMG electrodes (Fig. 5). For further description of the technical details for the analysis of the MMG signal and technical specifications of the two accelerometers, see the method section of the individual papers.

3.4.3. Intramuscular pressure

In *study II* and *III*, IMP was measured using an intramuscular transducer-tipped pressure catheter (Millar[®] Micro-Tip[®], Houston, Texas, USA). The IMP catheter was inserted in parallel to the fiber orientation into the central part of m. biceps brachii through a Teflon catheter (Venflon, Ø14G/2mm OD) (Fig. 5). After insertion, the Teflon catheter was withdrawn leaving the IMP catheter in the muscle. For further description of the technical details for the measurements of IMP, see the method section of the individual papers.

3.4.4. Blood pressure

Non-invasive beat-to-beat blood pressure (BP) was measured continuously using Finometer[™] Blood Pressure Monitor spectroscopy (Finapres Medical Systems BV – TNO TPD Biomedical Instrumentation, Amsterdam, The Netherlands) with a small cuff placed around the tip of the third finger of the contra lateral resting arm. BP was automatically corrected for hydrostatic pressure with respect to heart level and the concomitant BP changes in the finger. In *study II*, BP was measured in terms of systolic and diastolic BP. In *study III*, the mean arterial pressure (MAP) was calculated as diastolic (BP + (systolic BP – diastolic BP))/3.



3.4.5. Muscle tissue oxygenation

In *study II* and *III*, muscle tissue oxygenation of m. biceps brachii was measured continuously using near-infrared spectroscopy (NIRS) (NIRO 300, Hamamatsu Photonics, Hamamatsu City, Japan). The NIRS probe was placed on the belly of m. biceps brachii (Fig. 6). The length of the probe was placed parallel to the fiber orientation and the near-infrared detectors were placed centrally over the muscle belly, which had been identified by palpation during isometric contraction of the muscle. The distance between the light sources and the detectors was 4 cm providing a light transmission depth of ~ 2 cm beneath the skin. For further description of the technical details for the measurements of TO₂, see the method section of the individual papers.

Figure 6 – Placement of the NIRS probe on m. biceps brachii in *study II* and *III*.

3.4.6. Force and goniometer

In *study I*, the static MVC force for EDC and TRA was measured by strain gauge force transducers (EDC: Alpha Beam 250N, BLH Electronics, USA; TRA: P.M.H. Elektronik, Copenhagen, Denmark). In *study II* and *III*, a strain gauge force transducer (P.M.H. Elektronik, Copenhagen, Denmark) was used to measure the static MVC force and the force at the wrist exerted by the subjects during elbow flexion. In *study III*, the force standard deviation (SD force) was calculated as an index of steadiness. The elbow angle was measured using a biaxial electrogoniometer (XM65, Penny & Giles Biometrics Ltd., Gwent, UK) placed parallel to humerus and on the line between epicondylus lateralis and processus styloideus.

To enable comparisons of dynamic and static contractions at comparable workloads, the time-tension index has to be considered. The time-tension index is the integration of the force curve in the given muscle contraction, i.e. the area under the force curve. Valid comparisons of static and dynamic contractions are possible if the performed force level over a given period of time is identical. Thus, the muscular response during 1-min intermittent static and dynamic contractions is comparable within each force level 10% and 20% MVC as the time-tension index is identical. Comparisons of the mean muscular response over time due to sustained static, intermittent static, or dynamic contractions can also be assessed when considering the time-tension index, i.e. 1-min intermittent static or dynamic contractions of 20% MVC vs. 1-min sustained static contractions of 10% MVC.

3.4.7. Biofeedback

The biofeedback program (Aalborg University, Aalborg, Denmark) used in *study I* was designed as a graphical user friendly interface developed in LabVIEW™ (National Instruments®, Austin, Texas, USA) with a time wise perspective (Madeleine *et al.*, 2006) and based on individual biofeedback threshold levels. The threshold level of muscle activity used during computer work was determined from several individual trials run before initiating the experimental protocol. The threshold value was defined as the root mean square (RMS) value where the subject was able to reduce the level of muscle activity in the given feedback muscle sufficiently to change the biofeedback status. The RMS values of the high pass filtered (2nd-order Butterworth filter, $F_c=5$ Hz) and collected biofeedback source signal (either *EMG* or *MMG*) were computed over non-overlapping 1-s epochs. To implement the time wise perspective in the biofeedback method, the number of epochs was set to three. The biofeedback

program generated a squared trigger signal coded on two bits and sampled synchronously with the EMG and MMG analogue signals at 1 kHz. An RMS value of the last epoch being below or above the threshold value and less than three consecutive RMS values being above the threshold led to a 0 or 1 V trigger signal, respectively. An RMS value of the last epoch above the threshold led to a 3 V trigger signal, respectively. Biofeedback was then given to the subject if three consecutive RMS values were above the threshold value (Fig. 7 and 8). Biofeedback was presented either *visually* (change color bar on screen from red to green) or *auditory* (turn off generated tone (560 Hz sinusoid)). The duration of the biofeedback above threshold, i.e. amount of time where three consecutive RMS values were above the threshold value, was computed relatively to the 3 min recordings (%).

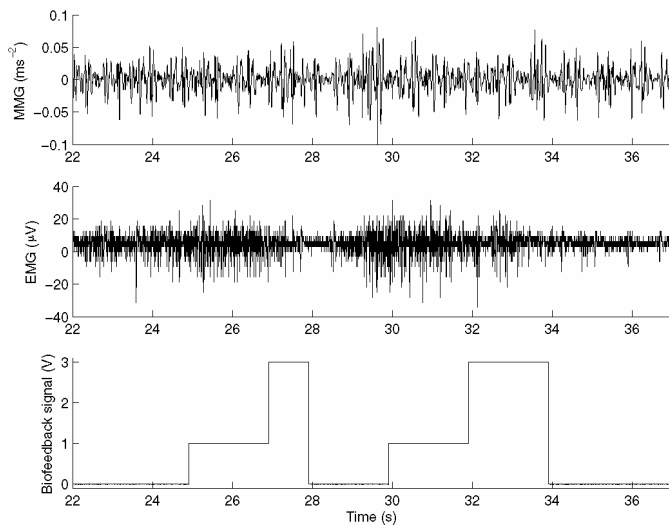
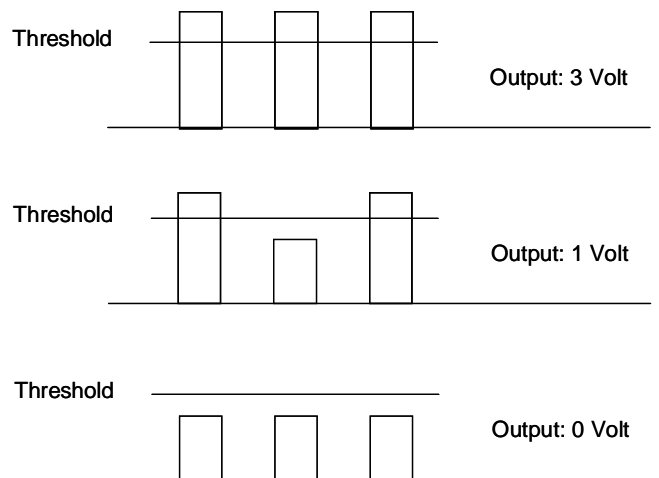


Figure 7 – Example of computer work with audio biofeedback from the right upper trapezius surface EMG signal. The filtered MMG (ms^{-2}), surface EMG signal (μV), and biofeedback trigger signal (V). Reprinted with permission from Taylor & Francis (Madeleine et al., 2006).

Figure 8 – Simplified illustration of how the biofeedback signal is generated. Three seconds with consecutive RMS values greater than the threshold value are needed for biofeedback to be generated (output = 3V). Otherwise, the output can be 1 V if the last RMS value is above the threshold or 0V if the last RMS value is below the threshold.



3.4.8. Rate of perceived exertion and subjective evaluation

In *study I*, the subjective evaluation of the usefulness of the feedback was also rated on a verbal 4-point scale with respect to the question “*was the biofeedback useful?*” by either answering *I fully agree* (1), *I partly agree* (2), *I partly disagree* (3), or *I fully disagree* (4) after ended work session. In *study III*, the subjects were asked to rate their perceived exertion in their m. biceps brachii every minute using the Borg scale from 0 (no perceived exertion) to 9 (maximum perceived exertion) (Borg, 1990).

3.4.9. Data collection and analysis

In *study I*, recordings of EMG were amplified, filtered, sampled, and recorded for later analysis using a custom build Medilog system (Bang & Olufsen Technology, Struer, Denmark). The MVC force was detected – in all studies – as the highest value measured over a 1 s period with a rolling window of 100 ms time shift. The contraction with the highest force level was considered to be the MVC, from which the loads for percentage of MVC were calculated (%MVC). In *study II* and *III*, recordings of force, EMG, MMG, IMP, rTO₂, and BP were amplified, filtered, sampled, and recorded simultaneously for later analysis using the data acquisition application Spike 2 (Cambridge Electronic Design, Cambridge, UK) (Fig. 9).

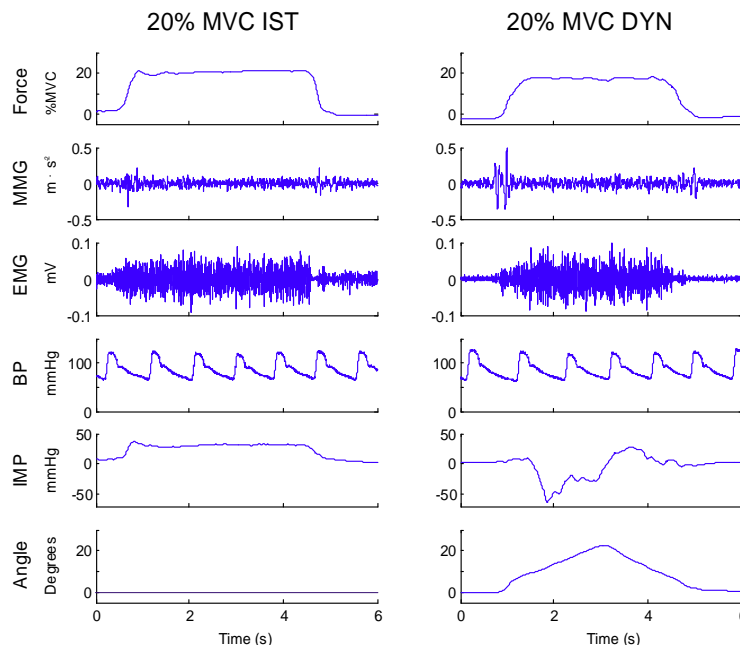


Figure 9 – The raw signals recorded from m. biceps brachii in one representative subject performing intermittent static (IST) and dynamic (DYN) elbow flexion at 20 %MVC. **Force**, (% MVC). **MMG**, muscle activity measured by mechanomyography ($m \cdot s^{-2}$). **EMG**, muscle activity measured by electromyography (mV). **BP**, mean arterial blood pressure (mmHg). **IMP**, intramuscular pressure (mmHg). **Angle**, elbow angle (degrees).

Study II: For comparisons between DYN and IST the mean values of the 2nd and 3rd s were analyzed for all variables. For the DYN session, the 2nd and 3rd s correspond to the concentric and eccentric phase of the contraction, respectively. The peak value of the electrogoniometer was used as the transition time between the concentric and eccentric phase in DYN. Subsequently, the mean of all 8 contraction periods was calculated for each subject and session. Correspondingly, each 4 s resting period underwent same procedure as when analyzing the contraction period. Following the last 4 s resting period, an additional period of 4 s rest was analyzed for TO₂. Additionally to the mean value, peak and nadir values in the 2nd and 3rd s were analyzed for IMP and TO₂. The applied filtering procedures resulted in the peak/nadir values to correspond to a mean across 44 ms. For comparisons between DYN and IST vs. SST, mean values for the entire 1-min contraction were analyzed for all variables. Furthermore, the IMP/EMG and MMG/EMG ratio were calculated in the units mmHg · mV⁻¹ and m · s⁻² · mV⁻¹, respectively. EMG and MMG were analyzed for root mean square.

Study III: For the sustained static elbow flexion at 10% MVC for 10 min, the force onset and offset were detected and mean values were calculated in 30 s windows. For the 5% MVC test contractions, mean values were computed in a 50 s time window where force level was constant to avoid the gross dimensional changes during build up and decay of the force. TO₂ was additionally measured during a 6 min recovery period immediately after termination of 10%MVC_{10min}. EMG and MMG were analyzed for root mean square and mean power frequency.

3.4.10. Statistics

The statistical analyses were performed by SPSS 12.0 and SigmaStat 2.03 (©SPSS Inc. 1989-2003, Chicago, USA). For further details on the applied statistical tests, see the statistical sections of the individual papers. Significance was tested at the 0.05 level in *study II* and *III*. Due to biofeedback being hypothesized to have a reducing effect on EMG muscle activity in *study I*, significance was tested at the 0.05 level in a one-tailed condition. P values below 0.1 were therefore considered significant. Acceptance of increased risk of type 1 error or a false positive result is legitimized as biofeedback offered to workers –if being effective- is regarded as beneficial. In general, the residuals were checked for normal distribution and variance homogeneity. Parametric statistics were preferred if data were normally distributed.

4. Results

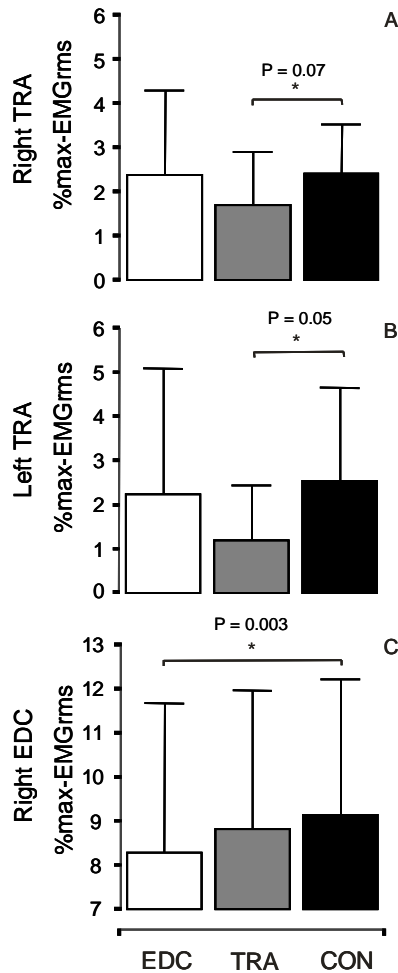
The results of the present thesis are described in detail in the 3 individual papers. The following result section summarizes selected results from the underlying papers and is divided into 2 parts; 1) results evaluating the effect of biofeedback on muscle activity (*study I*) and 2) results evaluating the muscular response during low-force dynamic, intermittent, and sustained static contractions (*study II and III*).

4.1. Study I

4.1.1. Control sessions

No significant differences were shown between the 3 control sessions regarding *time pressure vs. no time pressure* in muscle activity for either right or left TRA, or EDC. The *control* sessions were

therefore pooled and the means \pm SD were 2.4 ± 1.1 , 2.5 ± 2.1 , and 9.1 ± 3.1 %max-EMGrms for the right and left TRA and the EDC, respectively.



4.1.2. Control sessions vs. overall biofeedback from each muscle

Muscle activity in right TRA was reduced by $\sim 30\%$ when feedback was given from right *TRA* compared to *control* (1.7 ± 1.2 vs. 2.4 ± 1.1 %max-EMGrms, $P = 0.07$) (Fig. 10, A). In left TRA, muscle activity was significantly reduced by $\sim 50\%$ when feedback was given from right *TRA* compared to *control* (1.2 ± 1.2 vs. 2.5 ± 2.1 %max-EMGrms, $P = 0.05$) (Fig. 10, B).

Figure 10 – The muscle activity (%max-EMGrms) from a) right TRA, b) left TRA, and c) right EDC during biofeedback from right TRA or EDC or during no biofeedback (CONtrol sessions). Values are mean \pm SD, $n = 11$. Of note: the y axis does not origin at 0 in c).

Muscle activity in the EDC was also significantly reduced by ~ 10% when feedback was given from *EDC* compared to *control* (8.3 ± 3.4 vs. 9.1 ± 3.1 %max-EMGrms, $P = 0.003$) (Fig. 10, C). However, no significant effect was seen of feedback from *TRA* on muscle activity in EDC; nor of feedback from *EDC* on muscle activity of either right or left *TRA* (Fig. 10).

4.1.3. *Control sessions vs. overall biofeedback during time pressured and no time pressured working conditions*

A significant reduction in right and left *TRA* muscle activity was observed during computer tasks with *time pressure* performed with feedback compared to *control* (right: 1.9 ± 1.3 vs. 2.4 ± 1.1 %max-EMGrms, $P = 0.08$, and left: 1.5 ± 1.5 vs. 2.5 ± 2.1 %max-EMGrms, $P = 0.09$). No such significant reduction was observed in neither right nor left *TRA* when working with *no time pressure*. Only EDC muscle activity was significantly reduced during computer tasks performed with biofeedback compared with control both during *time pressure* (8.4 ± 3.2 vs. 9.1 ± 3.1 %max-EMGrms, $P = 0.002$) and during *no time pressure* (8.7 ± 3.2 vs. 9.1 ± 3.1 %max-EMGrms, $P = 0.08$).

4.1.4. *Differences between various biofeedback sessions: effect of feedback muscle, mode, and source*

When comparing the effect of biofeedback sessions with control sessions, the reduction observed in muscle activity depended on the biofeedback muscle and the working condition. Even though biofeedback tested overall had no effect on *TRA* during *no time pressure*, a more detailed analysis comparing the various biofeedback situations showed several significant findings.

In left *TRA* (Table 3), a significantly lower muscle activity ($P = 0.07$) was observed only when working with *no time pressure* and receiving biofeedback from right *TRA* compared to *EDC*. In EDC, a significantly lower muscle activity was observed (Table 3) ($P = 0.04$) only when working with *no time pressure* and receiving feedback from *EDC* compared to *TRA*.

A significantly lower muscle activity ($P = 0.09$) was observed in the left *TRA* during feedback through *MMG* compared to *EMG* when working with *no time pressure*. Moreover, a significantly lower muscle activity ($P = 0.03$) was observed in EDC, when receiving feedback through *EMG* compared to *MMG* during *no time pressure*. However, neither *auditory* nor *visual* biofeedback had an effect on muscle activity in any response muscle. The biofeedback sessions during *time pressure* showed no effect of any biofeedback factor.

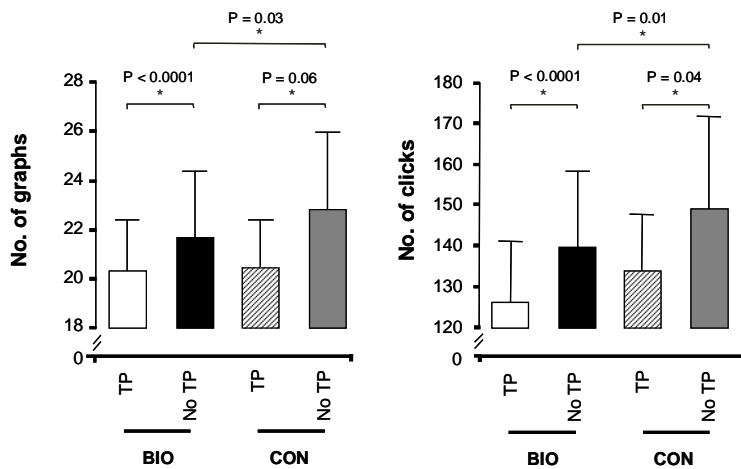
Table 3 – The muscle activity (%max-EMGrms) from right and left TRA and right EDC during the 14 biofeedback sessions.

			Time pressure		No time pressure	
			EMG	MMG	EMG	MMG
Right TRA	Audio	EDC	2.3 ± 1.9	2.3 ± 2.6	2.2 ± 1.5	2.7 ± 2.6
		TRA	1.7 ± 1.9	1.4 ± 1.2	1.8 ± 1.3	1.4 ± 1.2
	Visual	EDC	2.2 ± 2.2		2.5 ± 3.2	
		TRA	1.8 ± 2.1	1.4 ± 1.1	2.3 ± 2.0	1.6 ± 1.7
Left TRA	Audio	EDC	2.2 ± 3.4	1.7 ± 2.1	1.2 ± 1.2	3.0 ± 4.9
		TRA	1.3 ± 1.4	1.1 ± 0.9	0.8 ± 0.9	0.8 ± 0.8
	Visual	EDC	2.3 ± 4.2		2.9 ± 5.4	
		TRA	1.3 ± 1.6	0.6 ± 0.5	1.1 ± 1.1	2.5 ± 4.9
Right EDC	Audio	EDC	8.1 ± 3.3	8.2 ± 3.6	8.3 ± 3.4	8.6 ± 3.4
		TRA	8.6 ± 2.9	8.5 ± 2.9	8.6 ± 2.9	9.2 ± 3.6
	Visual	EDC	8.2 ± 3.6		8.3 ± 3.4	
		TRA	8.8 ± 3.3	8.6 ± 3.4	8.8 ± 3.5	9.4 ± 3.3

Values are mean ± SD, n = 11. **Audio**, auditory feedback; **Visual**, visual feedback; **EDC**, right m. extensor digitorum communis; **TRA**, right m. trapezius; **EMG**, electromyography; **MMG**, mechanomyography.

4.1.5. Productivity

During the *control* sessions with no feedback, less completed graphs were completed during *time pressure* compared with the productivity during *no time pressure* (20.4 ± 1.9 vs. 22.8 ± 3.2 graphs (P = 0.06)) together with less mouse clicks (133.7 ± 14.1 vs. 149.1 ± 22.5 clicks, P = 0.04) (Fig. 11). The same trend was evident in the biofeedback session, when comparing *time pressure* with *no time pressure* (p < 0.0001) (Fig. 11). Introduction of feedback during *no time pressure* resulted in ~ 5 % less completed graphs (21.7 ± 2.7 vs. 22.8 ± 3.2 graphs (P = 0.03)) together with ~ 7 % less mouse clicks



(139.6 ± 18.8 vs. 149.1 ± 22.5 clicks, P = 0.01) compared with no feedback during the control sessions (Fig. 11). Feedback during *time pressure* had no effect on productivity compared to that of the control sessions.

Figure 11 – The production of a) graphs and b) mouse clicks during standardized computer work in biofeedback sessions (BIO) and control session (CON) with time pressure (TP) or no time pressure (No TP). Values are mean ± SD, n = 11. Of note: the y axis does not origin at 0.

4.2. Study II

4.2.1. Kinetics and force

The measured MVC on the experimental day of IMP and rTO₂ did not differ significantly in both studies. As the target force performed in the sessions, test contractions, and fatigue protocol was determined from MVC, and recordings of force – during all sessions and contractions on the two experimental days – were not significantly different, the subjects performed the prescribed force level and working mode according to the designated sessions enabling comparison of TO₂ and IMP measurements.

The precision to follow the target movement of the elbow during DYN was analyzed for 7 subjects on the experimental day of IMP measurements (including all data from 0, 10, and 20 %MVC), and showed the concentric contraction to start at 0.11 (\pm 0.17) s (target: 0 s), the eccentric contraction to start at 2.14 (\pm 0.24) s (target: 2 s), and to end at 4.21 (\pm 0.33) s (target: 4 s). Target force during the sessions was met, as the force generated – mean of the 2nd and 3rd seconds of the contraction period on both days (n=32) – in DYN (10 and 20 %MVC) and IST (10 and 20 %MVC) was 10.2 \pm 0.1, 19.6 \pm 0.4, 10.4 \pm 0.2, and 20.3 \pm 0.2 %MVC, respectively. During SST, the generated force as a mean for the 1 min contraction period on both days was 5.1 \pm 0.3 and 9.8 \pm 0.3 %MVC for 5 and 10 %MVC, respectively.

4.2.2. EMG

EMGrms of the concentric phase in DYN was significantly higher (~1.5 fold) than of IST in the corresponding 2nd s of the contraction period (14.2 \pm 2.4 vs. 9.4 \pm 1.5 and 22.0 \pm 2.0 vs. 15.9 \pm 2.3 %max-EMGrms in 10 and 20 %MVC, respectively) while the differences in the 3rd s comparing eccentric with static contraction were not significantly different (Fig. 12, A). Mean EMGrms for SST was 6.7 \pm 1.2 and 9.5 \pm 1.5 %max-EMGrms in LOW and HIGH, respectively (Vedsted *et al.*, 2004). The corresponding overall mean values for IST and DYN were 5.8 \pm 0.9 and 6.8 \pm 0.9 %max-EMGrms, respectively, in LOW and 9.8 \pm 1.6 and 9.9 \pm 1.0 %max-EMGrms, respectively, in HIGH.

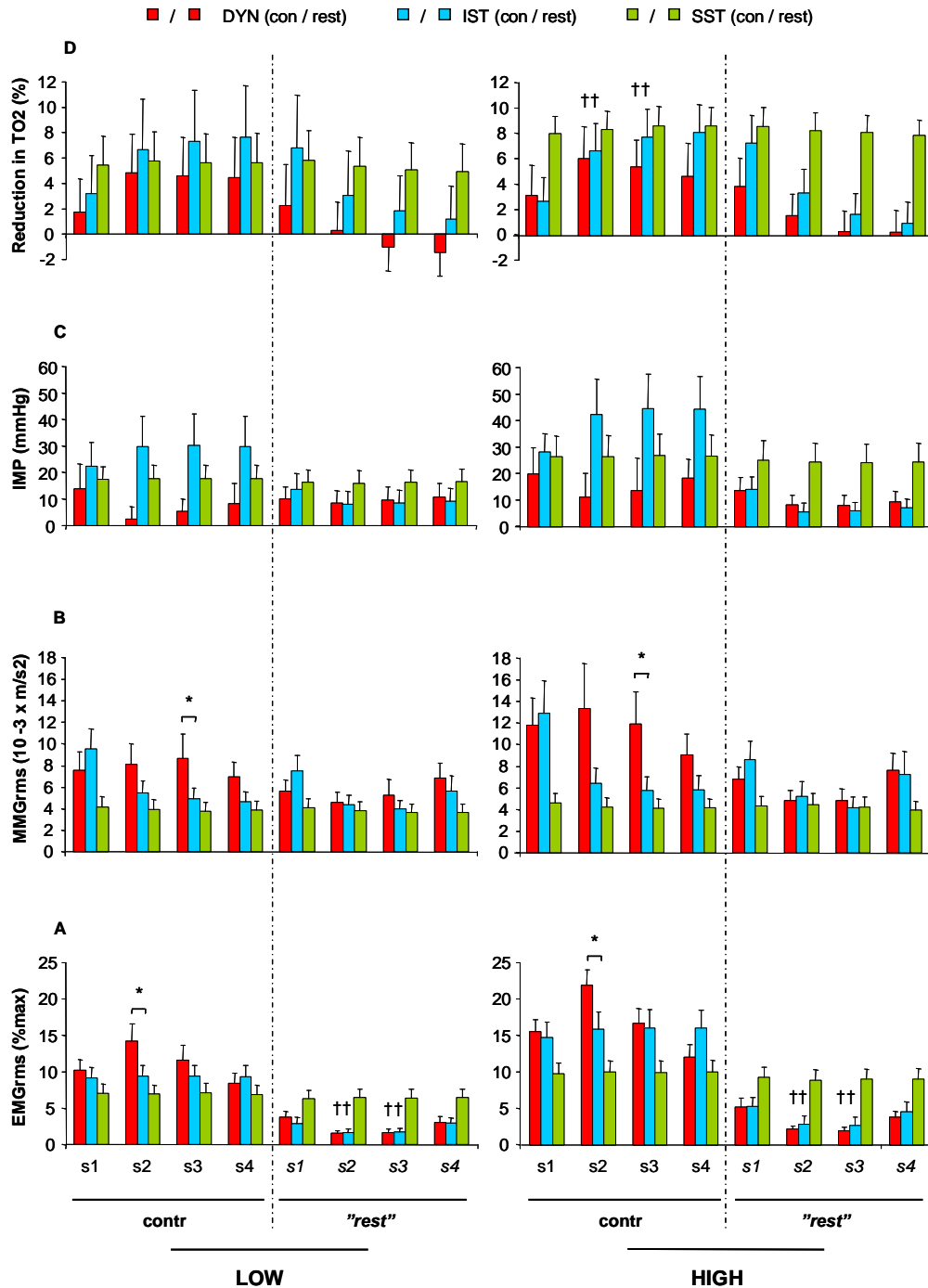


Figure 12 – Muscle activity measured by **A**) electromyography (EMGrms (%max)) and **B**) mechanomyography (MMGrms ($10^{-3} \cdot m \cdot s^{-2}$), **C**) intramuscular pressure (IMP (mmHg)), and **D**) reduction in muscle tissue oxygenation (rTO_2 (%)) recorded from *m. biceps brachii* during dynamic (DYN), intermittent static (IST), and sustained static (SST) sessions at LOW and HIGH force levels. **contr**; contraction period. **"rest"**; resting period. **s1, s2, s3, s4**; 1st, 2nd, 3rd, 4th s of contraction or resting period in DYN and IST. All seconds are a contraction period for SST. Values are mean \pm SEM. $n = 8$ in EMGrms and MMGrms at LOW and HIGH force level; and rTO_2 at LOW force level. $n = 7$ in IMP at LOW and HIGH force level; and rTO_2 at HIGH force level. * significantly different from DYN. † significantly different from baseline level recorded before initiating the work sessions.

4.2.3. MMG

MMGrms of the concentric phase in DYN during 10 and 20 %MVC tended ($p=0.05$ and $p=0.08$, respectively) to be higher (~1.5 and ~2.0 fold, respectively) than IST in the 2nd s of the contraction period (Fig. 12, B). In the eccentric phase in DYN, MMGrms was significantly higher (~1.5 and ~2.0 fold in 10 and 20 %MVC, respectively) than in IST in the corresponding 3rd s of the contraction period. No significant difference in MMGrms was found between any of the working sessions during the resting periods; the overall mean being $4.4 \pm 0.3 \cdot 10^{-3} \cdot \text{m} \cdot \text{s}^{-2}$. Mean MMGrms for SST was 3.9 ± 0.9 and $4.2 \pm 0.9 \cdot 10^{-3} \cdot \text{m} \cdot \text{s}^{-2}$ in LOW and HIGH, respectively (Vedsted *et al.*, 2004). The corresponding overall mean values for IST and DYN were 5.8 ± 1.1 and $6.7 \pm 1.4 \cdot 10^{-3} \cdot \text{m} \cdot \text{s}^{-2}$, respectively, in LOW and 7.0 ± 1.5 and $8.7 \pm 1.8 \cdot 10^{-3} \cdot \text{m} \cdot \text{s}^{-2}$, respectively, in HIGH.

4.2.4. IMP

IMP of the concentric phase in DYN was significantly lower than in IST in the 2nd s of the contraction period (2.3 ± 4.5 vs. 29.5 ± 11.7 and 10.9 ± 8.9 vs. 42.0 ± 13.1 mmHg in 10 and 20 %MVC, respectively) (Fig. 12, C). In the eccentric phase in DYN, IMP was significantly lower than IST in the 3rd s of the contraction period (~5 and ~2 fold in 10 and 20 %MVC, respectively). During the resting periods, there was no significant difference between the working modes; the overall mean being 7.0 ± 1.2 mmHg. Mean IMP for SST was 16.8 ± 4.9 and 25.4 ± 7.5 mmHg in LOW and HIGH, respectively (Vedsted *et al.*, 2004). The corresponding overall mean values for IST and DYN were 18.8 ± 8.0 and 8.5 ± 3.9 mmHg, respectively, in LOW and 23.8 ± 7.3 and 12.6 ± 4.9 mmHg, respectively, in HIGH.

Additional to the 1-s mean IMP values, peak and nadir values were calculated (Fig. 13). The peak IMP values in DYN and IST were not significantly different during 10 %MVC – nor in the resting periods. During 20 %MVC in the 2nd s of the contraction period, peak IMP was significantly lower in DYN vs. IST. However, in the resting period, peak IMP was significantly lower in IST vs. DYN in the 2nd s. The nadir values in the contraction period were all significantly lower during DYN than IST, and only during DYN, negative values were attained. The overall mean nadir and peak values for SST were 14.5 ± 4.4 and 15.7 ± 4.3 mmHg in LOW, respectively, and 22.0 ± 6.2 and 23.6 ± 6.2 mmHg in HIGH, respectively (Vedsted *et al.*, 2004).

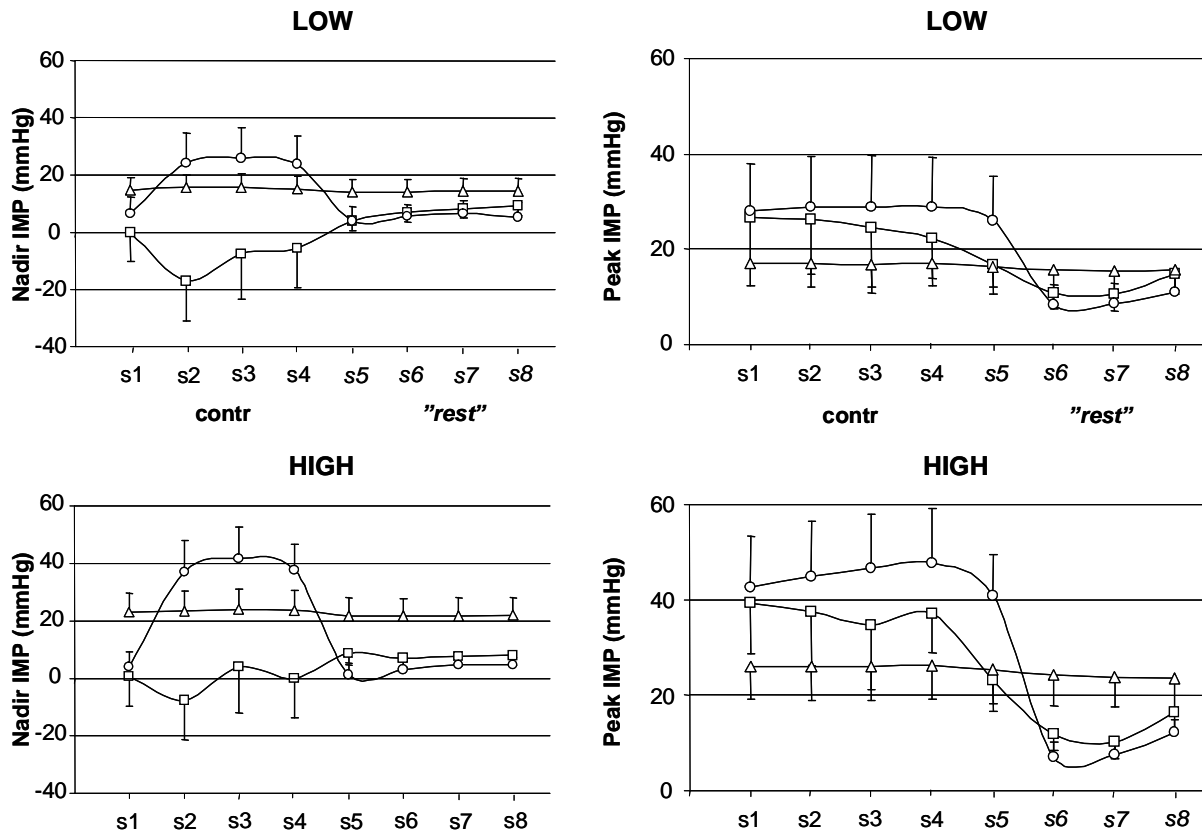


Figure 13 - Nadir and peak values of intramuscular pressure (mmHg) recorded from *m. biceps brachii* during dynamic (DYN), intermittent static (IST), and sustained static (SST) sessions at LOW and HIGH force levels. **contr**; contraction period. **rest**; resting period. All seconds are a contraction period for SST. Values are mean \pm SEM. $n = 7$. \square : DYN. \circ : IST. Δ : SST.

4.2.5. Muscle tissue oxygenation

No significant difference between DYN and IST was shown in rTO_2 during the contraction periods in any force level (Fig. 12, D). During 20 %MVC in the contraction periods, the rTO_2 in DYN, as well as IST, differed significantly from the baseline level recorded before initiating the work sessions. This was not the case for any of the 10 %MVC sessions. During the resting periods in both 10 and 20 %MVC, no significant difference was shown between DYN and IST in rTO_2 ; the overall mean being 0.9 ± 0.6 %. Mean rTO_2 for SST was 5.5 ± 2.3 and 8.2 ± 1.4 % in LOW and HIGH, respectively (Vedsted *et al.*, 2004). The corresponding overall mean values for IST and DYN were 4.7 ± 3.5 and 2.0 ± 2.5 %, respectively, in LOW and 4.8 ± 1.9 and 3.1 ± 1.9 %, respectively, in HIGH. For raw signals recorded during HIGH DYN, IST, and SST elbow flexion in one representative subject, see fig. 15.

During the prolonged resting period, the rTO_2 in DYN was significantly different from SST and above

baseline level in the low force level. During high force levels DYN was significantly different both IST and SST (Fig. 14 and 15). Only during SST, muscle tissue oxygenation kept on being reduced the prolonged resting period (Vedsted *et al.*, 2004).

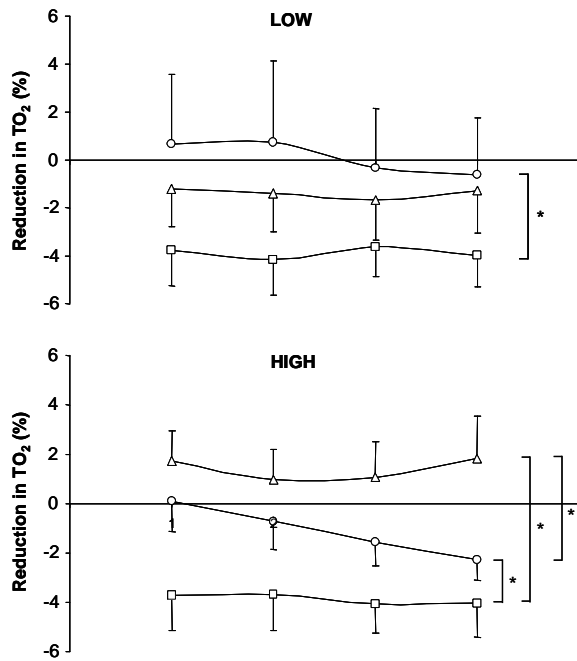


Figure 14 – Mean values of the reduction in muscle tissue oxygenation (%) recorded from *m. biceps brachii* during dynamic (DYN), intermittent static (IST), and sustained static (SST) sessions at LOW and HIGH force levels. □: DYN. ○: IST. △: SST. *, significantly different ($p < 0.05$). $n = 8$ in LOW force level. $n = 7$ in HIGH force level.

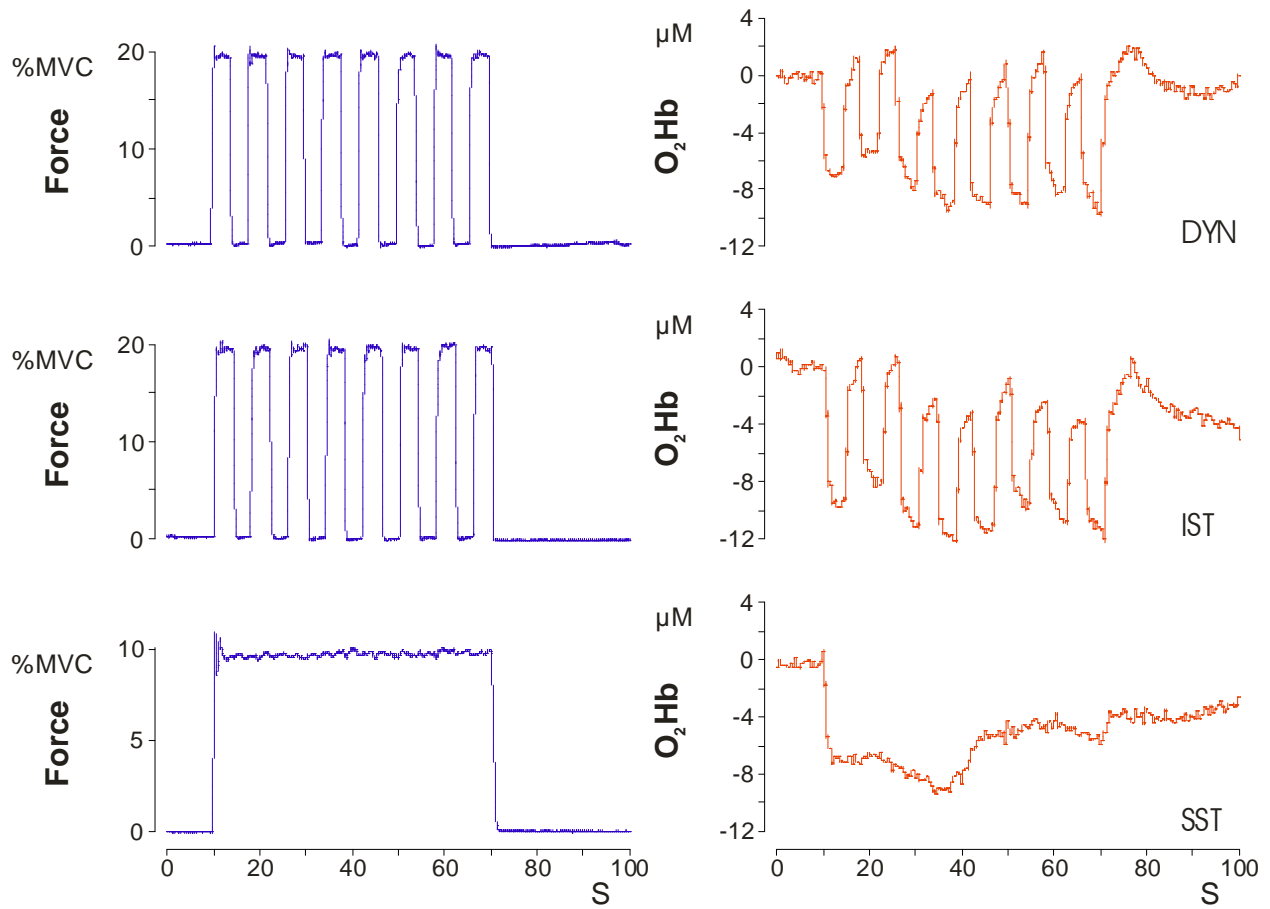
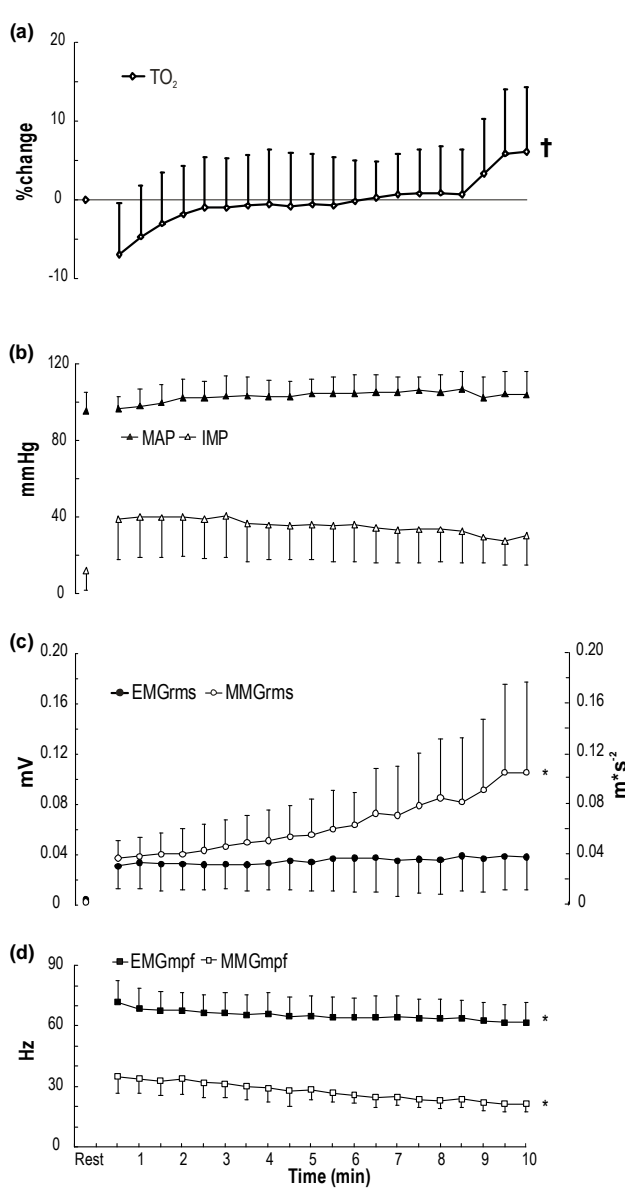


Figure 15 – The raw signals recorded from *m. biceps brachii* in one representative subject performing dynamic (DYN) (20 %MVC), intermittent static (IST) (20 %MVC), and sustained static (SST) elbow flexion (10 %MVC). **Force**, (% MVC). **O₂Hb**, muscle tissue oxygenation (μM).

4.3. Study III

4.3.1. 10 min sustained static contraction

During the 10%MVC_{10min} the performed force level, as a mean of the two experimental days, ranged between 10.1 and 10.3 %MVC, which showed that the task of meeting the target force of 10 %MVC was accomplished successfully. The index of steadiness was approximately 1.5 % and showed no significant change with time. MMGrms increased and EMGmpf and MMGmpf decreased during the contraction. The EMGrms was approximately 10% of the maximum EMGrms measured during the



MVC, and no general change was seen in time during (Fig. 16, c). The unchanged EMGrms combined with a pronounced increase in MMGrms resulted in a significant increase in MMGrms/EMGrms ratio from 1.6 (SD 1.1) in the first minute of the sustained static contraction to 3.1 (SD 1.5) at the end of the contraction.

At the onset of the 10%MVC_{10min}, the TO₂ decreased significantly from resting level to $-6.9 \pm 6.5 \%$ but subsequently there was a tendency to an increase with time ($p = 0.07$) and the mean TO₂ was $6.1 \pm 8.1 \%$ above resting level in the last 30 s of the sustained static contraction. Within 30 s after the termination of the sustained static contraction, the TO₂ increased further to $8.7 \pm 9.9 \%$ above resting level and stayed significantly increased for the first two minutes of the recovery (Fig. 16, a and 17). At 3 min recovery TO₂ was not significantly different from resting level.

Figure 16 – TO₂ (a), IMP, MAP (b), EMGrms, MMGrms (c), EMGmpf, and MMGmpf (d) during the 10% MVC sustained static contraction for 10 min (mean \pm SD). *, significant development over time, ($p < 0.05$). †, tendency over time ($p = 0.07$).

The average resting level of IMP measured before the 10%MVC_{10min} was 12.2 ± 10.4 mmHg. Initially, the IMP increased to a mean value of 38.8 ± 21.2 mmHg and remained above resting level throughout the contraction (Fig. 16, b). On group level no average time wise change was seen in IMP during the contraction but on an individual level, IMP decreased for three subjects, remained at the same level in two subjects, and increased for one subject. The resting level of IMP measured immediately after 10%MVC_{10min} was 10.2 ± 6.3 mmHg, which corresponded to the resting level measured before 10%MVC_{10min}.

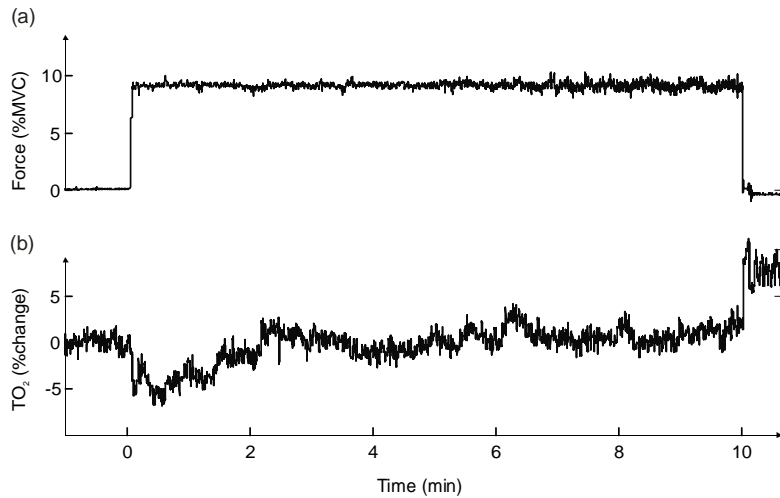
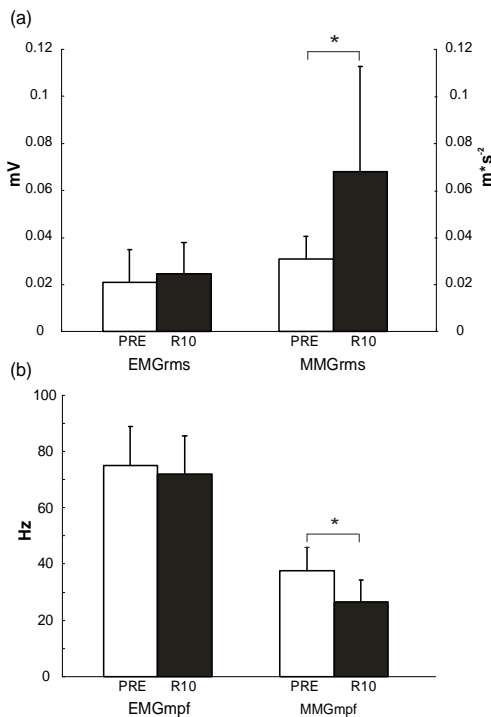


Figure 17 – Force (a) and tissue oxygenation (b) recorded for a representative subject during the 10% MVC sustained static contraction for 10 min.



During the 5% MVC test contractions, a significant increase in MMGrms was found PRE to R10 (Fig. 18, a). A significant decrease in both EMGmpf and MMGmpf from PRE to R10 was shown (Fig. 18, b).

Figure 18 – rms (a) and mpf values (b) of the EMG and MMG in the 5% MVC test contractions measured before (PRE) and at 10 min (R10) recovery (mean + SD). *, significantly different ($P < 0.05$).

5. Discussion

The main findings of the present thesis are; 1) EMG biofeedback is a potential tool for reducing activity in the muscle from which biofeedback is given during computer work; 2) EMG biofeedback has an effect on reducing muscle activity during time pressured work; 3) EMG and MMG activity were significantly larger during dynamic than intermittent static low-force contractions; 4) reduction in oxygen tension was similar during dynamic and intermittent static low-force contractions; 5) sustained vs. intermittent static low-force contractions resulted in larger reduction in oxygen tension as well as a larger MMG activity 6) sustained static-low force contractions for 10 min resulted in muscle fatigue but a reduction in oxygen tension did not underlie the decreased force-generating capacity.

5.2. Effect of biofeedback

Reductions in muscle activity due to biofeedback during standardized computer work was demonstrated for both TRA and EDC, suggesting an increase in the subject's awareness of unnecessary muscle activity levels, and thereby making the subjects reduce the muscle activity. This result is consistent with earlier EMG biofeedback studies (Poppen *et al.*, 1988; Nord *et al.*, 2001; Gerard *et al.*, 2002; Hermens & Hutten, 2002; van Dijk & Hermens, 2006). Auditory myofeedback presented to subjects performing a gross-motor task, showed an increase in the relative rest time and a decrease in muscle activity (Voerman *et al.*, 2004). Vollenbroek-Hutten *et al.* (2004) (Vollenbroek-Hutten *et al.*, 2006) showed significant changes in muscle activation pattern after myofeedback training. In a recent study, young adults succeeded in lowering their muscle activity following augmented biofeedback, whereas the elderly did not improve their motor control indicating motor skill learning to be age-dependent (van Dijk & Hermens, 2006). Biofeedback in the aforementioned studies was given when there was less time of rest than a preset period of time in the given muscle (Hermens & Hutten, 2002), by which the subjects became aware of insufficient muscle rest. The biofeedback method of the present study had a time wise perspective eliciting biofeedback if the muscle activity was above the threshold level for longer than a preset time period to initiate. Thereby, biofeedback was not only based on the amplitude level exceeding a given threshold level. However, the range of the individual threshold levels may still have initiated recruitment of the low threshold MU and thereby not unloading the MU fully. A reduction in muscle activity as little as 1-2% of maximal EMG muscle activity, as seen in the present study, may seem insignificant but physiologically it can have a favorable effect. The firing rate

of low-threshold motor units in trapezius has shown to increase with increasing contraction amplitude in the range of 1-10% of the maximal EMG activity (Westad *et al.*, 2004). Thus, a substantial reduction in muscle activity of such magnitude may also correlate with a reduction in the firing rate of the activated MU.

Considering the mode of contraction of TRA and EDC during computer work, some significant differences may be emphasized. TRA acts as a shoulder stabilizer and contracts primarily statically, whereas EDC contracts dynamically by being the prime mover during computer work. The distinct reduction in muscle activity observed in TRA and EDC when introduced to biofeedback may be due to differences in the contraction mode and thereby muscle activation pattern. Higher firing rates during a dynamic contraction was demonstrated during concentric wrist flexion at 30 and 60% of MVC compared with sustained static contraction at identical work load (Søgaard *et al.*, 1998). Interestingly, the increase in %MVC in dynamic contraction intensity was accomplished by recruitment of additional motor units rather than by increasing the firing rate as during static contractions, suggesting the MU activation strategy to depend on contraction mode. Therefore, it may be assumed that the smaller reduction in muscle activity in EDC compared to TRA is due to a limitation in the ability to change the MU activation strategy towards a more efficient strategy; i.e. increasing firing rate of the already active MU. In support of this notion, EMG vs. MMG showed to be the most efficient biofeedback source in the dynamically contracting EDC. MMG has been proposed to be a function of three components; 1) a gross lateral movement of the muscle at the initiation of the contraction that is related to the distinct regional distribution of the contractile elements, 2) smaller subsequent lateral vibrations generated at the resonant frequency of the muscle, and 3) pressure waves generated by the dimensional changes created by the fibers of the active MU (Barry & Cole, 1988;Orizio, 1993;Orizio *et al.*, 1996;Smith *et al.*, 1997). Since MMG therefore has been hypothesized to relate to the dimensional changes of the muscle fibers during lengthening and shortening contraction (Oster & Jaffe, 1980), a reduction in the number of crossbridge cycling per MU discharge during dynamic contraction when developing a given force may be complex. However, the less reduction in EDC muscle activity during biofeedback may also be due to the fact that the standardized computer task could not be performed with much less muscle activity than that of the control sessions.

Biofeedback may not only bring out beneficial outcomes, since a reduction in muscle activity in TRA with feedback from TRA caused an increase in muscle activity in other shoulder muscles, which

may result in just moving the musculoskeletal disorders to the synergists (Palmerud *et al.*, 1995). However, the reduction observed in the contra lateral TRA muscle activity in the present biofeedback study propose that biofeedback can reduce motor activity in other muscles than the muscle from which biofeedback is given. In line with this observation, a biofeedback study demonstrated that EMG biofeedback from TRA resulted not only in TRA muscle activity in a given work task but a general reduction of movements and adjustment of posture (Poppen *et al.*, 1988). Thus, the reduction in TRA muscle activity resulted in alteration of a number of motoric responses involved in the postural stabilization and not simply a change within the TRA itself, which was argued to be due to the TRA anatomical placement and function, i.e. TRA acting as a shoulder stabilizer during computer work. However, in another muscle region, a study demonstrated only little evidence of response generalization from the extensor to the flexor muscle of the forearm in violinists (Morasky *et al.*, 1983). In the present thesis, it was not possible to reduce the EMG activity level in EDC when feedback was given from TRA and vice versa, suggesting a limitation in the ability to transfer biofeedback from one muscle region to an effective change in motor control in another region.

5.3. *Effect of biofeedback during various working conditions*

Overall biofeedback during the *time pressured* working condition resulted in significantly lower muscle activity in the contra lateral TRA and the EDC compared to control, which opposes our hypothesis that feedback is more effective in the *non-time pressured* than in the *time pressured* working condition. Few studies have tested the effect of biofeedback during stressful vs. less stressful working condition. The present thesis is in contrast with a recent study investigating the effect of myofeedback on muscle activation patterns during a stress task and a typing task (Vollenbroek-Hutten *et al.*, 2006) where muscle relaxation level was lowest during the latter due to a higher myofeedback response. Likewise, biofeedback stimuli was introduced to subjects performing a gross-motor task with either 5-, 10-, or 20-s intervals, resulting in the 10-s interval being most effective in reducing trapezius muscle activity (Voerman *et al.*, 2004). The 5-s interval caused the highest level of trapezius activation perhaps due to a mental stress evoked by such relatively high number of feedback stimuli provided to the subject. Considering the productivity in terms of performed clicks and graphs, productivity was smaller during *time pressure* compared with *no time pressure* during both control and biofeedback sessions, which can be attributed to the design of the working condition with *time pressure*. However, it may suggest that

muscle activity was lowered by reducing the amount of work performed during computer work, as biofeedback resulted in a reduction of the muscle activity during *time pressure*. Within the *non time pressured* working condition, biofeedback resulted in smaller productivity compared to control, which supports the lower muscle activity observed during some biofeedback situations and the suggestion of lower work amount being a prerequisite if lower muscular load is the intention for a prime mover in a given work task. These results also bring support to the notion that there is little unnecessary EMG muscle activity that can be eliminated. A recent study, showed precision demand and mental pressure to have an effect on productivity in terms of a decreased time per mouse click (Visser *et al.*, 2004), indicating more clicks, i.e. higher productivity, for a given work period. However, high time pressure resulted in lowered productivity during high precision and mental demands during standardized computer work (Birch *et al.*, 2000).

5.4. Biofeedback as intervention for the prevention of WRMD

In the world of sports science, biofeedback applications have been utilized in an attempt to enhance athletic performance through biofeedback of heart rate, heart rate variability, maximal oxygen consumption, and ventilation (Zaichkowsky & Fuchs, 1988; Crews, 1992; Caird *et al.*, 1999). Essentially, this consists of top-level athletes learning more effective regulation of autonomic or neuromuscular functioning in accordance with the demands of their particular sport. The research in this field has demonstrated that even quite subtle changes issuing from biofeedback interventions can be enormously important, especially in elite events where small modifications can be of considerable importance to athletic performance. In the world of occupational health, small modifications in means of reduced muscle activity in the upper extremity muscles as seen in the present biofeedback study can as well have substantial effect in the interventions of preventing WRMD. A reduction of the mechanical peak load of the continuously recruited MU as well as a break in the prolonged MU activation may preclude a deteriorating metabolic response on a single muscle fibre level.

If biofeedback is to be used in the intervention of WRMD and implemented in practice, determination of whether the biofeedback induced improvement in motor control, which is long lasting, seems essential if biofeedback is to be efficient. Motor skill learning can be defined as internal processes taking place in association with biofeedback practice leading to a permanent change in the capability of movement (Winstein, 1991), emphasizing the importance of follow-up measurement

when evaluating the effect of biofeedback (van Dijk *et al.*, 2005). According to a systematic review of the effect of augmented biofeedback (van Dijk *et al.*, 2005), only one study reported a positive effect of motor learning (Marchese *et al.*, 2000). It was then suggested, that the effect of biofeedback intervention may depend on the duration and intensity. Short (1 day) and long termed (2 wks) effects of enhanced auditory feedback, demonstrated no significant differences in the effect of reducing typing force and EMG muscle activity (Gerard *et al.*, 2002). But no evidence of a long lasting effect of the short termed biofeedback training was put forth. However, subjects exposed to 4 month biofeedback training program, were able to continue reducing their typing force and EMG muscle activity during the given task (Gerard *et al.*, 2002). Therefore, it can be suggested that a long lasting effect of biofeedback on reducing EMG muscle activity is most efficient when introduced for subjects for a prolonged period. It can thus be suggested that the acute effect of the biofeedback performed in the present thesis could have resulted in a further reduction in EMG muscle activity if performed for more than the one experimental day. However, systematically investigation of the effect of different biofeedback intensities on reducing EMG muscle activity is lacking. Intensity can be varied in terms of frequency per week or day or even in the frequency of biofeedback stimuli during a single biofeedback training session, as was done in one study (Voerman *et al.*, 2004). Biofeedback intervention may also provide training in motor control and relaxation that is transferable to environments different from the occupational setting.

5.5. *The effect of muscle contraction mode*

It is generally recognized in the research of the development of WRMD, that variation in work tasks and muscle load are beneficial in order to prevent prolonged activation of the individual MU (Westgaard, 1988; Veiersted *et al.*, 1990; Kilbom, 1994; Sjøgaard *et al.*, 2001; National Research Council and the Institute of medicine, 2001; Mathiassen *et al.*, 2003). Variation can be induced through altered work/duty cycle time, different durations of the contraction and relaxation period, varied levels of required force development, and varied awareness and mental demands. The physical variation in occupational practice may be implemented by job enlargement where workers rotate between assembly tasks, which in itself are repetitive and not recommended for a prolonged period of time (Moller *et al.*, 2004). The assumption that more physical variation is recommended in the prevention of WRMD has been based on physiological studies demonstrating that muscle fatigue is alleviated by increased

variation and epidemiology studies investigating different occupations with varying or repetitive work settings. Different contraction modes, i.e. sustained static, intermittent static, and dynamic contractions, can as well be considered as an intervention strategy of creating physical variation at the myofibrillar level. Strategies of MU recruitment pattern has been shown to be task and contraction mode related (Moritani *et al.*, 1987; Riek & Bawa, 1992; Enoka, 1995; Sjøgaard *et al.*, 1998) as force development during movement tasks imply a greater reliance on MU recruitment rather than MU firing rate. Thus, variation in terms of different contraction modes can be beneficial if the stereotyped activation of the low-threshold MU is to be broken and thereby not aggravating a muscular response that can provoke muscle disorder.

Investigating the muscular response in the m. biceps brachii in study II and III is due to the muscle being very assessable making surface recordings of EMG, MMG, TO₂ possible. Moreover, the muscle is well-studied in the literature and the measured muscular response is believed to be transferable to other muscles of the human skeletal system. Evaluation of the muscular exposure of 5 and 10 % MVC force level during more standardized circumstances was chosen as this force level is comparable to the muscular load measured in TRA and EDC during computer work in *study I*. 10% MVC has also been observed as the peak load in TRA during computer work (Sjøgaard & Jensen, 2006). An evaluation of the physiological response during 10% MVC performed both intermittently statically and dynamically can give recommendation for the use of computer input devices. As mean and peak work loads of 20 – 30% MVC frequently are observed in occupational settings such as industrial sewing, meat cutting, and post office work, the muscular load of 20% MVC was evaluated (Sjøgaard & Jensen, 2006).

5.5.1. *Electromyography and mechanomyography*

The present thesis demonstrated EMG and MMG muscle activity to be higher during the DYN compared to IST contraction periods. The larger EMG and MMG activities suggest larger energy consumption during dynamic contractions, as EMG activity has shown to correlate linearly with oxygen consumption in m. biceps brevis and m. brachioradialis (Praagman *et al.*, 2003). Likewise, earlier studies have shown that EMG amplitude signal increases in proportion to the oxygen uptake during dynamic exercise (Bigland-Ritchie & Woods, 1974; Jammes *et al.*, 1997; Jammes *et al.*, 1998). A close relation between MMG and oxygen consumption rate has also been demonstrated during cycle

ergometry (Stout *et al.*, 1997). MMG activity averaged over the entire contraction period was also higher during both DYN and IST compared to that of SST. Thus, the acute electrical activity observed in a non-fatigued muscle in this thesis supports the fatigue studies that compared the development of fatigue induced by different modes of contraction (Fenn, 1923; Bridges *et al.*, 1991; Vedsted *et al.*, 2003; Hostens *et al.*, 2004) suggesting the acute activity to predict faster fatigue development with dynamic than intermittent static contractions. Similarly, fatigue development induced either by static or dynamic contractions resulted in a more pronounced decline in the force generating capacity in a dynamic test contraction (Hostens *et al.*, 2004) suggesting a higher activation level required to develop a given force when performed through a movement task. It has been assumed that during voluntary contraction, the MMG origin is intrinsic to the muscle (Stokes & Blythe, 1995; Sogaard *et al.*, 2006) and accordingly has been considered as a tool to follow motor MU activation strategy (Orizio *et al.*, 2003). As discussed above, the MMG signal detected at the muscle surface is hypothesized to not only reflect MU activity but also to relate to the dimensional changes of the muscle fibers during lengthening and shortening contraction (Oster & Jaffe, 1980). The MMG may therefore also origin from the process of the attachment and detachment. The higher MMG activity during DYN vs. SST is therefore consistent with studies showing both a higher MU firing rate and a strategy towards additional MU recruitment during dynamic vs. static contractions for a given force development (Enoka, 1995; Sogaard *et al.*, 1998). Furthermore, if cross bridge lifetime is less during muscle shortening compared with static contractions, it may be speculated that additional cross bridges take place during dynamic contractions, which then can be reflected in the MMG signal. The difference observed in MMG between SST and IST can be due to the exerted force variations in the transition between contraction and relaxation period in IST eliciting modulation in firing rate and the number of recruited MU (Denier van der Gon JJ *et al.*, 1985; Pilegaard *et al.*, 2000). During low-force and low-velocity contractions of the biceps muscle, it has been shown that even though the number of active MU is similar during static, concentric, and eccentric contractions, the discharge rate decreases from the concentric to the eccentric phase of the contractions (Sogaard *et al.*, 1996). However, the number of crossbridge cycling per MU discharge may also differ considerably between static and dynamic as well as between concentric and eccentric, which also would predict a difference in MMG amplitude. In line with these results, our data in general showed a larger MMG activity during dynamic than static contractions and in particular, eccentric contractions presented significantly larger MMG amplitude

than static contractions. This could be explained by the lower MU discharge rate during eccentric contraction causing an unfused tetanus by a more distinct mechanical twitching that result in larger MMG amplitude. Another possible candidate to MMGrms changes is the recruitment of fast MU during eccentric efforts (Linnamo *et al.*, 2003), which has been reported for higher velocity contractions. Given the more superficial location of the fast motor units in biceps brachii (Clamann, 1970) these may influence more directly the MMG generation process. A velocity-related derecruitment of slow MU with selective activation of fast MU during eccentric contractions was found and suggested to contribute to an increased MMG activity during the eccentric phase (Nardone & Schieppati, 1988).

As the EMG is considered as an estimation of the neural drive, the MMG can be considered the mechanical counterpart and, thus, the MMG/EMG ratio provides an estimation of the electromechanical efficiency (Barry *et al.*, 1990). During the eccentric phase in DYN of 20 %MVC, the MMG/EMG ratio was significantly higher than that in IST indicating that a given EMG activity may result in a larger number of the cross bridge cycling, e.g. attachment and detachment, in DYN than IST. In accordance with this interpretation, it may be suggested that at higher contraction intensities the electromechanical efficiency is higher during dynamic vs. static contractions at identical time-tension products. Of note is, however, the distinction between electromechanical and metabolic efficiency. The higher EMG activity in the concentric compared with the static contraction phase, is indicative of a larger oxygen consumption during dynamic than static exercise protocols, and indicate a lower metabolic efficiency during dynamic than static contractions. As mentioned above, this would *per se* induce larger reduction in muscle oxygen tension in dynamic than in static exercise sessions.

Based solely on the level of muscle activity in dynamic compared to static contractions performed with corresponding duty cycle and time-tension products, it may not be beneficial to work dynamically as recommended in the occupational setting, as low-force dynamic contractions performed for a prolonged period of time may result in faster and more pronounced muscle fatigue, which then can lead to an impairment of muscle function.

5.5.2. Tissue oxygenation and intramuscular pressure

During muscular work, the blood flow is closely related to the metabolism and consequently muscle homeostasis. To meet the energy demand of the contracting muscle, blood flow increases with

increasing work intensity (Radegran & Saltin, 1998). An elevation in IMP has shown to be a consequence of increasing contraction intensity, which then may result in compression of the vascular bed emphasizing the importance of a low IMP for a well-balanced muscle homeostasis. The IMP response has been investigated during static and dynamic contractions in rabbit tibialis anterior muscles and human m. supraspinatus (Degens *et al.*, 1998; Sjøgaard *et al.*, 2004). Both studies demonstrated IMP to correlate positively with force during static contractions, and to be higher during dynamic vs. static contractions at corresponding force levels. The larger IMP compressing the vascular beds and impeding blood flow, which together with larger energy consumption during dynamic contractions, would result in a larger reduction in oxygen tension than in static contractions. The results of this thesis, however, demonstrated no difference in the muscle tissue oxygen tension during contraction periods when subjects contracted dynamically and intermittent statically at identical time-tension products. The IMP response was significantly smaller during dynamic vs. intermittent static contractions, which regards mean as well as peak values. Since no significant differences in BP were seen between the contraction modes, the smaller IMP may imply that the blood flow during the dynamic contractions was larger than that of intermittent static contractions. A larger blood flow will result in a larger oxygen supply and thus, compensate for a larger energy turnover (oxygen consumption) during dynamic compared to intermittent static contractions at identical time-tension products. This may explain the similar oxygen tension in DYN and IST in spite of the oxygen consumptions most likely being higher during DYN than IST. However, the reduction of muscle tissue oxygenation averaged over the entire contraction period was more than 2-fold larger in SST than that of DYN for both force levels and IST for the high force level, which is in line with the 2-fold higher IMP during SST compared with the overall mean value for DYN. These results confirm the suggested relationship between an increased IMP and impediment of the microcirculation (Jarvholm *et al.*, 1988) and thereby hampering the oxygen supply. Conversely, no difference in IMP between SST and IST were shown in spite of differences in muscle tissue oxygenation.

Different muscle types can explain the inconsistency in the results of IMP of this thesis and the afore-mentioned studies of (Sjøgaard *et al.*, 2004) and (Degens *et al.*, 1998). The muscle compartments, architecture, and compliance being distinct between m. biceps brachii and m. supraspinatus could suggest the IMP response to be muscle dependent (Jensen *et al.*, 1995b). With the IMP being related to the shape and location of the muscle, high IMP occurs in cylindrical and deeply

located muscles. As the m. biceps brachii is located superficially with no surrounding muscles or bony walls compressing it and the m. supraspinatus is located deeply, higher IMP can be expected in m. supraspinatus. The measuring site within m. biceps brachii may as well have an impact on the IMP measurement. Regional differences in muscle oxygenation during exercise was found in the gastrocnemius muscle and was also suggested to be related to architectural alterations in the muscle and blood vessels (Miura *et al.*, 2004). Accordingly, the lower IMP during DYN than IST and SST may only be evident for muscles similar to the architecture of the human m. biceps brachii. Negative nadir IMP values in DYN may as well have facilitated blood flow and resulted in an oxygen tension above baseline. The better oxygenation of the muscle tissue observed during dynamic contractions may then be explained by the mechanisms similar to the venous pump in the legs. Concentric contractions have shown to produce a subsequently higher blood flow than passive venous compression (Zhang *et al.*, 2004). The mechanism was explained in terms of the rhythmic muscle contraction repeatedly emptying the veins and facilitating perfusion of the skeletal muscle (Folkow *et al.*, 1970; Folkow *et al.*, 1971; Radegran & Saltin, 1998; Shiotani *et al.*, 2002). The results of the present study may then be seen in the light of the contracting muscle creating an increase in pressure difference in the active muscle due to the mechanical effect of muscle pumping action and a local vasodilatation. Contraction induced accumulation of potassium and lactate in the extracellular space has been shown to cause a vasodilation of the vascular bed (Lindinger & Sjogaard, 1991; Lash, 1996; Shoemaker *et al.*, 1998). Such a condition may result in a larger muscle blood flow in the dynamic situation. In line with the results of this thesis, a decrease in IMP following active muscle contractions vs. passive venous compression was reported (Styf, 1990), which (Zhang *et al.*, 2004) then is speculated to cause the greater blood flow during active contractions in their study. However, whether the muscle pump is the primary regulator of blood flow is still questionable, as local hyperemia may occur independently of vasodilation (Sheriff *et al.*, 1993). A recent study, demonstrated that the mechanical action of rhythmic maximal tetanic skeletal contractions reduces peak muscle perfusion and concluded that vascular conductance under such conditions is accomplished exclusively via dilation of the vascular bed due to an endothelial-derived relaxation factor and accumulation of metabolites (Dobson & Gladden, 2003). Nevertheless, evidence of such regulation of blood flow during low-force contraction is still lacking.

As a repeating duty cycle is an intrinsic element in both DYN and IST, the muscle pump activity in dynamic and intermittent static contractions may be speculated to be similar. The present

thesis, however, showed that the fluctuations in IMP are larger – in terms of larger differences between nadir and peak IMP values – during DYN than in IST, which may result in more beneficial conditions for the blood flow. Hence, the duration of higher pressure is longer during intermittent static vs. dynamic contractions. Oscillations in IMP during dynamic contractions were also shown in the m. vastus lateralis (Radegran & Saltin, 1998). Such beneficial conditions for the blood flow created by the repeating duty cycle in DYN and IST were not present in SST due to the mechanical characteristics of a sustained static contraction. Consequently, the conditions for the oxygen supply are attenuated, which also was demonstrated in the larger reduction in muscle tissue oxygenation for SST than that of DYN and IST. Interestingly, in spite of discrepancies in the relative IMP values between static and dynamic contractions in different muscles as mentioned above, the IMP/EMG ratio was smaller in dynamic vs. intermittent static contractions, which is in concert with the results reported previously for the m. supraspinatus (Sjøgaard *et al.*, 2004), indicating a common finding of lower IMP for a given muscle activity during dynamic vs. static contractions.

During the prolonged resting period at the end of each working session, there was a difference between the contraction modes in recovery of muscle tissue oxygenation as the oxygen tension was above baseline following the dynamic contractions at both low and high force levels. During the high force level, the muscle tissue oxygenation differed significantly between SST and IST, as intermittent static contractions also resulted in oxygen tension above baseline. The physiological response during the prolonged resting period suggests better oxygenation of the muscle tissue following contractions comprised of a repeating duty cycle. A change in duty cycle has shown to affect the metabolic rate and blood flow (Dodd *et al.*, 1994; Hogan *et al.*, 2003). Blood flow response to intermittent exercise has shown to depend largely on the contraction frequency and duty cycle, with blood flow being lower at a given power output when contraction frequency is increased (Hoelting *et al.*, 2001). Muscle oxygen uptake and energy turnover was shown to be elevated during dynamic contractions when contraction frequency was increased together with an increased blood flow (Ferguson *et al.*, 2001). A recent study suggested that blood flow was independent of the relaxation time provided that the duration between muscle contractions was sufficiently long (Shoemaker *et al.*, 1998). However, blood flow may be compromised by contraction frequency if the time spent between contractions is reduced enough (Hoelting *et al.*, 2001). By increasing the frequency or prolonging the contractile phase of the duty cycle, the overall muscle perfusion may be affected detrimentally resulting in inadequate oxygen

delivery and the contractility to be attenuated. However, by increasing the non-contractile phase additional time for perfusion and tissue oxygenation would be admitted. In all, it may be the physiological responses during the resting periods in dynamic work that attribute to the better recovery and thereby a better prevention of muscle disorders compared to static contraction.

In line with the fact that a repeating duty cycle may have a protective effect on fatigue development, are the results of a low-frequency electrical stimulation study (Lexell *et al.*, 1993), which investigated whether muscle fiber degeneration was related to the pattern and frequency of stimulation. Rabbit fast-twitch muscles were stimulated for 9 days with pulse trains ranging in frequency from 1.25 to 10 Hz and contracted either sustained or intermittent statically. Muscles subjected to 10 Hz intermittent stimulation showed significantly less degeneration than muscles stimulated with 5 Hz continuously, although the aggregate number of impulses delivered was the same. However, increased activity of oxidizing free radical-mediated reactions have also been proposed to play a major role in the development of muscle damage (McArdle & Jackson, 1997). Oxidation of saturated fatty acids in the sarcolemma and of proteins including Na^+/K^+ -ATPase and Ca^{2+} -ATPase can take place and subsequently result in membrane damage and dysfunction of the ion pumps due to an increase in the reactive oxygen species (Close *et al.*, 2005). During intermittent exercise, the energy supply is suggested to vary enormously due to the oscillation in the IMP, as observed in this thesis, which can induce a large oxygen flux or oxidative burst through the muscle tissue, which can attribute to a formation of reactive oxygen species (Close *et al.*, 2005; Visser & van Dieen, 2006). Intermittent activity performed dynamically or statically may therefore trigger mechanisms that are less beneficial for the muscle function.

With regard to the acute intramuscular pressure response and muscle tissue oxygenation during dynamic, intermittent static, and sustained static low-force contractions, the effect of cycle time and duty cycle seems more important in the prevention of WRMD than the contraction mode being dynamic or static, as reductions in muscle tissue oxygenation were similar during DYN and IST, but 2-fold larger during SST than DYN and IST. However, a less beneficial metabolic response during intermittent work is the risk of the formation of reactive oxygen species. Based on the present results, dynamic activity has to be considered in a broader sense and include not only isolated dynamic contractions. Dynamic activity must include varying movements performed with varying frequency and duration.

5.6. The effect of sustained static contraction on muscle fatigue

As the reduction in muscle tissue oxygenation in SST (*Study II*) was up to 2-fold higher than that observed in DYN or IST, it would be expected that the fatigue development induced by a sustained static contraction performed for 10 min, would be due to further reduction in the muscle tissue oxygenation. Muscle fatigue during the 10% MVC sustained static contraction was evidenced by changes in the EMG and MMG activity. However, the fatigue development could not be explained by reductions in muscle tissue oxygenation, since the oxygenation returned to resting level within the first minute of the contraction.

The unchanged mean IMP with time and even a decrease for three subjects was seen during 10%MVC_{10min} is in contrast to the correlation previously reported between increasing EMG and IMP (Sadamoto *et al.*, 1983a;Crenshaw *et al.*, 1997). However, most recently a constant or decreased IMP was also reported in m. supraspinatus during a prolonged low-force contraction (Sjøgaard *et al.*, 2004). In this thesis, the unchanged IMP is reflected in the tissue oxygenation that was only below resting level at the onset of 10%MVC_{10min} and tended to increase above resting value during the contraction indicating the metabolic dilatation with time being sufficient to maintain whole-muscle oxygen level. Since the MAP as well as the IMP remained constant throughout the 10%MVC_{10min}, together with the absence of the rhythmic skeletal pump, a metabolically induced decrease of the vascular resistance was probably inducing an increase in blood flow during the contraction and thereby preserving the tissue oxygenation, even in spite of expected increased oxygen consumption. The lack of increased IMP and the tendency to an increase in tissue oxygenation could also suggest a decreased biceps brachii muscle force during 10%MVC_{10min} elbow flexion. Usually, EMGrms increase when a constant force is maintained over time, therefore the unchanged EMGrms may indicate a change in the load sharing between the elbow flexor muscles during the contraction. In line with this, the distribution of activity among elbow flexor synergist muscles has shown to change with time during a prolonged static contraction at 20% MVC (Hunter *et al.*, 2003).

The oxygen availability in the muscle as measured by the present NIRS method seems to be sufficient during the 10%MVC_{10min}, but in spite of this it cannot be ruled out that the microcirculation to single muscle fibers may have been reduced. Muscle tissue oxygenation determined by the NIRS method indicates the balance between oxygen delivered to and consumed within the tissues (McCully & Hamaoka, 2000;Esaki *et al.*, 2005). A limitation of the method is that it measures tissue oxygenation

in a volume of several cm^3 (Ferrari *et al.*, 1997) and consequently does not represent oxygenation in the whole limb but only at a certain location of the muscle. Single muscle fibers could have been metabolically exhausted following the $10\% \text{MVC}_{10\text{min}}$ but not being detectable by the sensitivity of the NIRS method. However, muscle tissue oxygenation of forearm flexor muscles measured by the NIRS was closely reflected in the exercise intensity and the metabolic rate determined by ^{31}P magnetic resonance spectroscopy, illustrating the validity and potential advantages of the NIRS for measuring muscle oxidative metabolism during exercise (Boushel *et al.*, 1998). The notion that the same few low-threshold MU are continuously activated during prolonged low-force contractions (Olsen *et al.*, 2001; Adam & De Luca, 2003), and thereby having a relative high energy turnover, is supported by studies using the microdialysis technique. Anaerobic metabolic activity was shown in the upper trapezius muscle during repetitive contractions of approximately 10% MVC (Ashina *et al.*, 2002; Rosendal *et al.*, 2004a) and ascribed to local obstruction of the blood flow and possibly due to inhomogeneous MU activation (Rosendal *et al.*, 2004a). Interestingly, oxygen availability has been found to play a major role in the regulation of low threshold MU recruitment and firing frequency (Moritani *et al.*, 1992). A recent study demonstrated a decrease in the tissue oxygenation in the forearm following 45 min computer work (Heiden *et al.*, 2005), which then could attribute to an anaerobic response. Further, the almost 4-fold increase in IMP from approximately 10 mmHg at resting level to 30-40 mmHg during $10\% \text{MVC}_{10\text{min}}$ may be of concern when such low-force levels are sustained for prolonged durations. In experimental animal models, muscle capillary perfusion decreased in a near-linear relationship with muscle tissue pressure, and the number of perfused capillaries was halved at a tissue pressure of approximately 40 mmHg (Hartsock *et al.*, 1998). Moreover, pressures above 30 mmHg maintained for 8 hours induced necrotic changes in the muscle (Hargens *et al.*, 1981). Despite sufficient oxygen availability observed in the present thesis, it can not be concluded that a 10% MVC sustained static contraction is a safe level of workload if performed over an entire work day. Due to the intramuscular response observed in *study II*, intermittently statically or dynamically contractions performed for prolonged period of time may prevent or postpone fatigue attributable to more beneficial conditions for the blood flow. However, intermittent isometric contractions for 16 min resulted in fatigue development reflected in an impaired force production (Wigmore *et al.*, 2005) and likewise, a limitation in the blood flow did not underlie the fatigue development. Given the response of tissue oxygenation, IMP, and blood flow during sustained and intermittent static fatiguing contractions

discussed above, an unequivocal mechanism underlying the fatigue development can not be determined.

5.7. *Consequences of metabolic overload*

In spite of the substantial reduction in muscle activity observed in *study I* or the varied muscle activity pattern due to cycle time and duty cycle observed in *study II*, the metabolic homeostasis may still be challenged, since force development has shown to depend on the inter-firing interval of the initial 2-3 firings, double discharges – short inter-firing intervals lasting < 20 ms also termed doublets – can assist in maintaining force even after the firing frequency is reduced (Sjøgaard *et al.*, 2000). With the rate of Ca^{2+} release from the sarcoplasmic reticulum being linearly related to and controlled by the inter-membrane charge movement (Melzer *et al.*, 1986), an accumulation of Ca^{2+} may be the result of doublets. Moreover, as a stereotyped recruitment of the low-threshold MU could not be entirely precluded in the biofeedback set-up of *study I*, the MU can consequently be overloaded mechanically and metabolically. Accumulation of metabolites, electrolyte disturbances, and altered Ca^{2+} homeostasis is the result of repeated activation of the muscle. Such metabolic response may also be the scenario in the surroundings of the low-threshold MU. Prolonged elevated Ca^{2+} concentrations in the cytosol can have detrimental effects on morphological changes and muscle damage (Jackson *et al.*, 1984; Favero, 1999; Berchtold *et al.*, 2000). Ca^{2+} ions have shown to activate intracellular phospholipases (Jackson *et al.*, 1984) and proteases (Belcastro, 1993; Belcastro *et al.*, 1998), which are enzymes that in turn degrade cellular lipids, proteins, and membranes. Therefore, inhomogeneous activation of muscle exerting low forces may be a risk factor (Sjøgaard *et al.*, 2000) for developing WRMD. Recently, some studies reported doublets in the EDC during both double clicking (Sjøgaard *et al.*, 2001; Thorn *et al.*, 2005) single mouse clicks (Thorn *et al.*, 2005) suggesting a probability of doublets also during the standardized computer task of this biofeedback study as a given task was to be performed, and thereby a requirement of a given force development.

Prolonged muscle activity can also induce metabolic disturbances due to other factors than just the requirement of a given mechanical task. Exposure to time pressure and high mental demand have been identified as a major risk factor for developing musculoskeletal disorders during computer work due to consequential elevated muscle activity and raised secretion of cortisol and catecholamine (Lundberg *et al.*, 1994; Melin & Lundberg, 1997). Schleifer *et al.* (2002) (Schleifer *et al.*, 2002)

proposed a hyperventilation theory of job stress that attempted to explain a variety of biologically plausible mechanisms by which stress factors may increase the risk of musculoskeletal disorders. Respiratory alkalosis is a result of hyperventilation, which may arise because of time pressure. Respiratory alkalosis triggers a number of physiological responses that may have deteriorating impact on muscle performance. Peripheral vasoconstriction is a response to alkalosis (Guyton & Hall, 2000) or enhanced sensitivity to sympathetic activity, which then will reduce blood flow to upper extremities and cause a exacerbated decrease in muscle tissue oxygenation due to stress during prolonged repetitive work. Recently, decreased local oxygen saturation was demonstrated in the forearm during more vs. less stressful computer mouse work (Heiden *et al.*, 2005). In spite of not measuring such physiological responses during the *time pressured* working condition in the present biofeedback study, such a physiological response is expected to make biofeedback less effective during the *time pressured* working condition.

5.8. Contraction mode as intervention for the prevention of WRMD

Considering the proposal of the MMG signal to relate the dimensional changes during contraction and perhaps to the process of the attachment and detachment between the myofilaments during contraction (Oster & Jaffe, 1980), changes in the MMG signal during low force contractions could indicate impairments in the force generation at the myofibrillar level. It has been suggested that LFF is a situation where increased activation is required to achieve a given force in the presence of excitation-contraction coupling failure (Stokes, 1993). Low-force contractions have been shown to cause LFF that is characterized by a slow rate of recovery of the force-generating ability (Bystrom & Kilbom, 1991; Blangsted *et al.*, 2005). LFF has also shown to occur in the forearm muscle during computer mouse work (Jensen *et al.*, 1999b). The fatiguing protocol of 10% MVC, which is a workload often performed in various occupations, suggests that low-frequency fatigue can occur in the daily work life, which consequently requires an increased activation of MU in terms of additional MU recruitment or increased MU firing rate. Such increased load of the MU can then trigger disturbed metabolic homeostasis that may initiate the development of WRMD through degeneration of the structural components of the skeletal muscle. If disturbed Ca^{2+} homeostasis is the result of continuous activation of the muscle and limitations in the local blood supply and metabolic removal, the morphological structures of the muscle can be challenged due to cell membrane degradation. Degradation of protein in

skeletal muscle has shown to be enhanced upon increased intracellular free calcium concentration (Belcastro, 1993;Westerblad *et al.*, 2000) initiating a further protein breakdown that can lead to WRMD. Sufficient recovery relative to the contraction period may, however, constitute a preventive factor in the development of WRMD. Beneficial recovery can be implemented by breaks or intermittent work pattern in terms of varied cycle time and duty cycle, when taking into account the physiological response of IMP and tissue oxygenation during dynamic and intermittent static contractions observed in this thesis. A possible accumulation of metabolites in the contraction phases may be recovered in terms of a metabolic flush out during the relaxation phases postponing or even preventing the fatigue development such metabolic accumulation may attribute to.

Some epidemiological studies have shown that static muscle activity and a low rate of short unconscious interruptions in EMG activity (EMG gaps) are relevant for the development of complaints. Subjects in a group of manufacturing workers, who showed fewer EMG gaps in their trapezius muscle activity, were at higher risk to develop trapezius myalgia (Veiersted *et al.*, 1990;Veiersted *et al.*, 1993). Such EMG gaps were found to coincide with derecruitment and substitution of MUs (Westgaard & De Luca, 1999). Recently, it was showed that MU derecruitment is not only promoted by short depressions in contraction amplitude, but also by increased contraction levels (Westad *et al.*, 2003). It appears that force variation in either direction promotes derecruitment of MUs. It was demonstrated that individual MU, which have recruitment thresholds below the performed force level, presented firing patterns with silent periods following a voluntary increase in muscle activity. It was concluded, that the order of recruitment was thereby reversed relative to other MU concurrently active, which may represent a motor control adaptation to reduce fatigue in low-threshold MU during sustained contractions. Therefore, variation in MU recruitment pattern can not only be elicited by intermittent contractions performed both statically and dynamically but also through dynamic and static contractions performed at various force levels. A single optimal contraction mode, which results in low muscle activity, low intramuscular pressure response, and a well-balanced muscle homeostasis, can not be determined as a continuously activated muscle – regardless of contraction mode – will develop muscle fatigue. Earlier recommendations for effective prevention of WRMD, such as an acceptable low MVC force level or a limitation in the exposure time of continuously muscle activation, can not solely prevent muscle fatigue and muscle disorders. A combination of the contraction modes performed through varied cycle time

and duty cycles at different force levels can be effective to obtain an as varied muscular response as possible, which may attribute effectively to the prevention of WRMD.

6. Conclusion

The following conclusions can be drawn from the present thesis:

AIM 1:

- Biofeedback is a useful tool in reducing muscle activity when working with standardized computer tasks. Biofeedback enables computer workers to decrease the prolonged level of muscle activity in m. trapezius by 30 – 50% and m. extensor digitorum communis by ~ 10%, which may have protective effect on work-related musculoskeletal disorders.
- During time pressured conditions, overall biofeedback caused lower muscle activity in the contralateral TRA and the EDC compared to control but not during the non-time pressured working condition.

AIM 2:

- *Dynamic* low-force contractions caused the EMG and MMG activity to be significantly higher than *intermittent static* low-force contractions. Intramuscular pressure was lower during *dynamic* vs. *intermittent static* low-force contraction, which may account for the reduction in oxygen tension not being larger during *dynamic* vs. *intermittent static* contraction.
- *Sustained static* low force contractions caused lower mean MMG activity than *dynamic* and *intermittent static* low-force contractions. Larger mean reductions in muscle tissue oxygenation was demonstrated during *sustained static* vs. *intermittent static* and *dynamic* low-force contractions, which may be due to the higher mean intramuscular pressure during *sustained static* contractions compared with that during *intermittent static* and *dynamic* contractions.
- *Sustained static* low-force contractions for 10 min induced acute fatigue development reflected by changes in the EMG and MMG signal. However, muscle tissue oxygenation did not underlie this fatigue development despite a 4-fold increase in the intramuscular pressure.

- No single contraction mode meet the criteria of a low muscle activity as well as a low metabolic load in terms of low intramuscular pressure and consequently optimal conditions for the blood flow and the muscle tissue oxygenation to prevent muscle fatigue over time. Thus, the hypothesis of the existence of a single optimal contraction mode for preventing muscle fatigue and WRMD was rejected.

Conclusively, when formulating criteria and efficient intervention strategies for the prevention of work-related musculoskeletal disorders due to repetitive low-force work, biofeedback as well as a combination of various muscle contraction modes performed through different time and force exposure profiles is recommended.

7. Perspectives

Results from the investigation of the effect of biofeedback accentuate the efficiency of biofeedback as a useful tool in reducing muscle activity in upper extremity muscles. In future biofeedback studies, systematical investigation of both the short and long termed effect of biofeedback on reducing EMG muscle activity is to be performed. Variations in the biofeedback duration and intensity would be important aspects to shed light on. The present thesis investigated the acute muscular response during dynamic, intermittent static, and sustained static low-force contractions through measurements of electrical and mechanical activity, muscle tissue oxygenation, and intramuscular pressure. The results emphasize the importance of variation in several aspects. Variation in time in terms of cycle time and duty cycle and variation in contraction mode performed through varied force profiles is recommended as an efficient intervention strategy for the prevention of WRMD. However, prolonged exposure to different low-force contractions modes in combination with different time exposure profiles is still to be systematical investigated. Further, it would be of relevance to investigate if intervention in terms of variation in the mentioned aspects would be beneficial for workers on sick-leave with diagnosed musculoskeletal disorders. Such results could elucidate on the relationship between the recommended strategy and the development of musculoskeletal disorders and whether such intervention can promote an earlier return to work.

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