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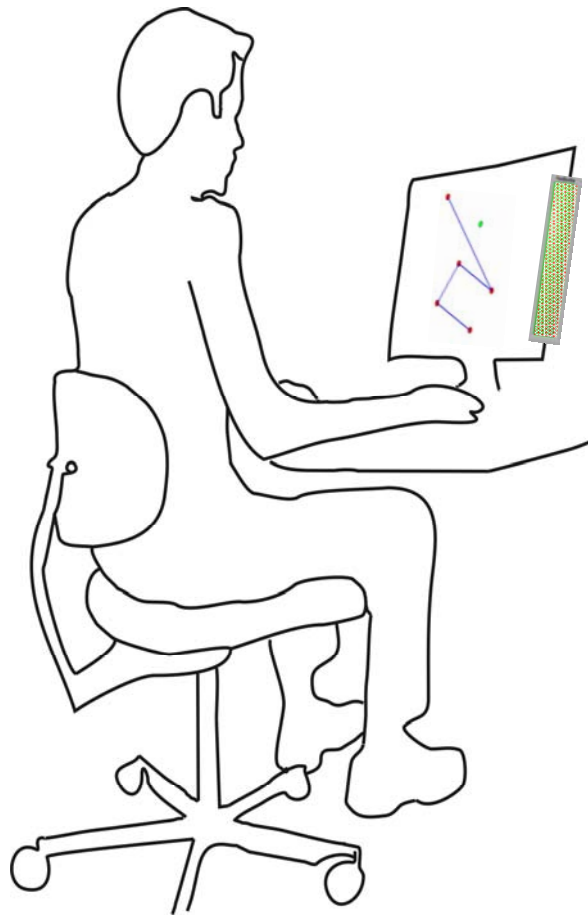
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On advanced biofeedback and trapezius muscular activity during computer work



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This dissertation is based on the following peer-reviewed articles referred to by their Roman number in the text.

Study I: A. Samani, A. Holtermann, K. Sjøgaard and P. Madeleine, "Active pauses induces more variable electromyographic pattern of the trapezius muscle activity during computer work," *J Electromyogr Kinesiol.*, vol. 19, pp. e430-437, 2009. doi: 10.1016/j.jelekin.2008.11.011.

Study II: A. Samani, A. Holtermann, K. Sjøgaard and P. Madeleine, "Experimental pain leads to reorganisation of trapezius electromyography during computer work with active and passive pauses," *Eur J Appl Physiol*, vol. 106, pp. 857-66, 2009. doi: 10.1007/s00421-009-1083-9.

Study III: A. Samani, A. Holtermann, K. Sjøgaard and P. Madeleine, "Effects of eccentric exercise on trapezius electromyography during computer work with active and passive pauses," *Clin. Biomech.*, vol. 24, pp. 619-625, 2009. doi:10.1016/j.clinbiomech.2009.05.011.

Study IV: A. Samani, A. Holtermann, K. Sjøgaard and P. Madeleine, "Advanced biofeedback from surface electromyography signals using fuzzy system," *Med. Biol. Eng. Comput.*, vol 48, pp.865–873, 2010. doi:10.1007/s11517-010-0651-9.

Study V: A. Samani, A. Holtermann, K. Sjøgaard and P. Madeleine, "Active biofeedback changes the spatial distribution of upper trapezius muscle activity during computer work," *Eur. J. Appl. Physiol.*, vol 110, pp.415–423, 2010. doi:10.1007/s00421-010-1515-6.

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Preface

The present studies were carried out at Centre for Sensory-Motor Interaction (SMI), Aalborg University, in the period from 2007 to 2010. Current PhD stipend was co-funded by Aalborg University, National Research Centre for the Working Environment and Danish research ministry.

I am most grateful to all co-authors for their contributions and for a fruitful collaboration. Especially, I wish to express my sincere gratitude to Professor Pascal Madeleine for his supervision, inspiration and encouragement to my projects as well as my co-supervisors Karen Søgaaard and Andreas Holtermann. I also thank Knud Larsen, for his guidance throughout the implementation of the software package performing the experiments. I would also like to thank all my colleagues at Centre for Sensory-Motor Interaction for providing a friendly, inspiring and competitive research environment. Particularly, I thank Asbjørn Binderup for his collaboration during the data collection for study III. I also appreciate the patience and cooperation of all volunteers who participated in the experiments of the current PhD study.

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To my lovely parents who supported me, encouraged me and prayed for me

List of abbreviation

DOMS: Delayed onset muscle soreness
EMG: Electromyogram
EVA: Exposure variation analysis
MfRI: Membership function readjustment interval
HD-EMG: High density
MMG: Mechanomyography
PeSaEn: Permuted sample entropy
RMS: Root mean square
RRT: Relative rest time
SaEn: Sample entropy
SEMG: Surface electromyography
VAS: Visual analogue scale
VDU: Video display units
WMSD: Work-related musculoskeletal disorders

English Summary

The prevalence of work-related musculo-skeletal disorders (WMSD) in the shoulder region related to prolonged periods of muscle activity is high among computer workers. Ergonomic studies focused on improvement of workstation design do not confirm that improving work posture or workstation designs permanently reduces the risk for neck-shoulder pain in computer workers.

Introducing an effective work-rest schedule has been found to be an inexpensive and advantageous approach to reduce WMSD problems associated with computer users. However, a pure rest breaks (passive pause) within the working time are not found effective for preventing neck-shoulder pain. Active pauses as a brief increase in the exerted force at normal working state have been introduced as an alternative leading to other issues such as the timing and the type of such pauses.

Biofeedback is shown to be effective in changing the activity pattern of the trapezius. However; numerous risk factors are suggested to play a role in development of WMSD. As such, while high electromyographic (EMG) activity usually is regarded as a risk factor, it has also been reported that a high activity level can contribute to facilitation of electrolyte and fluid balance, improving blood circulation and thus, preventing blood pooling for muscular tissues. Thus, the biofeedback system should be able to cope with such uncertain risk factors. Fuzzy inference system was suggested in this PhD study as a main core of decision-making process.

The interactions of muscle pain and soreness with pause type were also investigated as it gives an insight into the transduction, transmission, and projection of nociceptive input in response to such pauses. Two modalities of experimental muscle pain as injection of hypertonic saline and delayed onset muscle soreness was induced on healthy subject during computer work.

Active pause resulted in more variable pattern of muscular activity in trapezius which is suggested to be a potentially beneficial effect preventing sustained monotonous activity of motor units. However, this

beneficial effect was deteriorated in presence of muscle pain or soreness. Additionally, excessive number of active pause may lead to muscle fatigue effect depicted by increased EMG amplitude. Biofeedback system was developed to decide about the appropriate timing between successive active pause. This system could merge multiple source of information and features of muscular activity under a fuzzy based decision making core. Active pauses triggered by biofeedback system resulted in higher irregularity over trapezius as a whole although lower regularity was observed in descending part of trapezius. Spatial changes in trapezius activity were induced underlining that a reorganisation of trapezius muscle activation pattern during computer work is possible. The implemented biofeedback system made a benchmark for further studies on prevention of WMSD using the developed system.

Dansk Sammenfatning

Udbredelsen af arbejdsrelaterede muskuloskeletale lidelser (WMSD) i skulderregionen i forbindelse med lange perioder med muskelaktivitet er høj blandt computerbrugere. Ergonomiske undersøgelser, der fokuserer på en forbedring af udformning af arbejdspladserne, bekræfter ikke, at en forbedring af arbejdsstilling eller arbejdsstationdesign reducerer risikoen for nakkesmerter hos computerbrugere. Indførelse af en effektiv arbejds-hviletid har vist sig at være en billig og fordelagtig måde at nedbringe WMSD problemer i forbindelse med computerbrugere. Dog er rene hvilepauser (passive pauser) inden for arbejdstiden ikke fundet effektive til at forebygge nakke-skulder smerter. Aktive pauser som en kort stigning i den udøvende kraft i normal arbejdstilstand er blevet foreslået som et alternativ. En anden problemstilling er den rette timing til at gennemføre disse pauser. Biofeedback har vist sig at være effektiv til at ændre aktivitetsmønstret for trapezius-musklen/-musklerne. Da WMSD er kendt for at have en multi-faktoriel ætiologi, er den indflydelsesrige risikofaktor dog lidt usikker. Mens en høj EMG aktivitet normalt betragtes som en risikofaktor, er det også blevet rapporteret, at et højt aktivitetsniveau kan bidrage til lettelse af elektrolyt- og væskebalancen, da det forbedrer blodcirkulationen og dermed forhindrer blodophobning i muskelvæv. På den måde kan biofeedback systemet klare disse usikre data. Fuzzy inferens systemet blev foreslået i dette Ph.D. studium som en primær kerne i beslutningsprocessen. Samspelet mellem muskelsmerter og ømhed med pausetype blev også undersøgt, da det kunne give et indblik i transduktion, transmission, og projektion af nociceptiv input i forbindelse med sådanne pauser. Vilkårerne for eksperimentel muskelsmerte som injektion af hypertontisk saltvand og forsinket start af muskelømheds er fremkaldt på raske personer under computerarbejde. Aktiv pause resulterede i flere variable mønstre af muskulær aktivitet i trapezius, som foreslås at have en potentiel gavnlig virkning til at forhindre vedvarende monoton aktivitet af motorenheder. Imidlertid kunne denne gavnlige effekt ikke måles ved muskelsmerter eller ømhed. Derudover kan et højt antal aktive pauser have en kumulativ trættende virkning, som resulterer i

øget EMG amplitude. Biofeedback-systemet blev udviklet til at beslutte om den hensigtsmæssige timing mellem den efterfølgende aktive pause. Dette system kan flette flere kilder til information og funktioner af muskulær aktivitet under en fuzzy baseret beslutningsproceskerne, som resulterede i højere uregelmæssighed over trapezius som helhed, selv om lavere regelmæssighed blev observeret i den faldende del af trapezius. Det implementerede biofeedback-system dannede grundlag for yderligere undersøgelser om forebyggelse af WMSD.

Introduction

Work-related musculo-skeletal disorders (WMSD)

WMSD (e.g. carpal tunnel syndrome, rotator cuff tendinitis, trapezius myalgia, low back pain) are among the most prevalent disablers of working staff [111]. WMSD are major occupational concern in the industrialized countries, especially in the lower back and neck and shoulder area. According to workers' compensation claims and occupational safety and health act (OSHA) 200 log data, the reported incidence of these disorders has been increasing dramatically since the early 1980s [20] and they affect workers in almost all occupational setups. In Denmark, about 20% of working population with neck-shoulder or low back pain had at least one spell of long-term sick leave during two-year follow-up [62]. WMSD are characterized as multi-factorial to indicate that a number of risk factors (e.g., physical, work organizational, psychosocial, individual, and socio-cultural) contribute to causing these disorders [10].

Physiological mechanism and biomechanical principle underlying muscle injury and pain which may lead to WMSD during high intensity dynamic contraction have been discussed quite thoroughly [33, 117]. However, knowledge about risk factors and underlying physiological causes for WMSD in sedentary jobs remains lacking. Nevertheless, persons in jobs with high physical exposure report more WMSD than those in "light" jobs, not necessarily, because their job has caused an injury but because symptoms from previous injury are aggravated in heavy jobs [75]. Therefore, the distinction between causative and symptom-aggravating factors at work is difficult to make. Among the sedentary occupations, the prevalence of WMSD is specially pronounced in computer workers [14, 70, 71].

Increased amount of computer work

Trends in working life in the industrialized world suggest a general move towards different jobs and task having more similar exposures, and towards less physical exposure variation in those jobs and tasks [92]. As

such, computer work is regarded as the most typical type of this sort of jobs. Nowadays computer work and in particular video display units (VDU) have become widespread for routine use, in almost all work places and at home [1]. Particularly computer workers performing intensive computer mouse use for long periods are at increased risk for WMSD [65, 68].

The high prevalence of WMSD in computer workers has stimulated a variety of preventive scientific initiatives. Especially ergonomic studies focused on improvement of workstation design [43]. However, scientific investigations do not support that improving work posture or workstation designs reduces the risk for neck pain in computer workers [27].

Physical and psychosocial risk factors to WMSD among computer users

Non-neutral wrist, arm and neck postures, the work station design and the duration of computer work, particularly VDU work, as well as psychological and social factors, such as time pressure and high-perceived workload, are reported to be involved in the development of WMSD symptoms [41, 110, 124]. A descriptive model of contributing risk factors for WMSD among computer users has been suggested [132]. According to this model, the risk factors could be categorized into physical load e.g. muscular load, posture and visual demand, psychosocial factors and mental stress and finally individual differences e.g. sex and working techniques.

The commonly used method to assess load within this field has been force and electromyography (EMG) which represent both the physical and mental demands of work [137]. To perform precise tasks, where sustained static contractions often along with repetitive hand and arm movements are required to stabilize one joint region e.g. shoulder girdle, it is likely that low threshold motor units are firing continuously until the muscle is relaxed completely [56].

Persistent firing of low threshold motor units during quasi-static sustained contraction is so-called “Cinderella hypothesis” [56] is supported by findings which show an increased percentage of type I fibers in women with trapezius myalgia [73]. Additionally, long-time static work is suggested to lead to “moth eaten”

or “ragged red” type I fibers. Ragged red” fibers are closely related to repetitive assembly work [54]. All these phenomena could be due to a reduced micro circulation which, in turn, may have been due to an inability to relax the muscles. Particularly in computer work, intramuscular EMG studies showed continuously active motor units throughout the recording time [44, 72, 144].

EMG gap frequency and muscular relative rest time (RRT) have been used in several studies to quantify the activation pattern [58, 127]. EMG gap and RRT respectively, represent the prevalence and the proportion of periods with muscle activity below a predefined threshold level for a certain time limit. Association of low RRT and EMG gaps with a higher risk of WMSD symptoms has been suggested in the neck/shoulder region [55, 126].

The relationship between pattern of muscle load and level of discomfort and pain has not attracted lot of attention during computer work. Most of the recommendations emphasize modification of posture as the mainstay of WMSD risk reduction [48]. Positive association between sitting at work, non-neutral posture (i.e. flexion) and neck and shoulder (i.e. flexion and abduction) and risk of developing WMSD symptoms in neck/shoulder has been found [5, 110, 124]. The position of the mouse away from the midline of the body causes an unsupported forward flexed arm and abducted externally rotated shoulder for mouse users [2, 25]. As such higher abducted arm has been found to be associated with WMSD symptoms in neck area [24]. Additionally, the horizontal surface of conventional mouse requires strong pronation in the forearm which is close to the extreme of what is anatomically possible. Sometimes computer users lift their elbow to facilitate the forearm pronation. This will cause muscle tension about the shoulder girdle [78] and/or supporting the whole forearm on the table top in front of the operator was found to be of fundamental importance for reducing the static trapezius load when using keyboard and mouse [2].

Despite all these findings, improvements of work posture and workstation designs have not been effective for preventing neck-shoulder pain in computer workers [18].

A correlation between visual discomfort and pain in the neck and the shoulder has been found [1]. This correlation is incorporated with the findings, which show an increase in trapezius muscle load due to eye movements from a rest position [125]. The parameters such as screen flicker, lighting levels the number and strength of colours used in a multi-colour display and glare profoundly affect on visual discomfort [1]. Positioning of monitor screen with respect to eye level can affect on loading of neck and shoulder muscles [45]. In the studies of current dissertation, a standard office workstation was used to perform the experiments so the effect of such risk factors was tried to be controlled.

Stress is defined as a non-specific response to a factor or condition causing several physiological and/or psychological reactions [132]. Different psychosocial factors have been suggested as risk factors for WMSD symptoms in the neck/shoulder region, for instance, high job demands, low decision latitude, time pressure, mental stress, job dissatisfaction, high workload and lack of social support from colleagues and superiors [132].

Mental exposure can interact with muscle activity in two ways i) through the connection between mental stimuli and activation of motor neurons leading to increase of tension ii) the activation of stress hormones such as catecholamins and cortisol which may impede renewal of the cells due to their catabolic influence [117]. Particularly during computer mouse work, mental pressure has been found to contribute substantially to increase the muscular activity in trapezius, wrist extensors and flexor [129].

Individual factors have been shown to be important explaining the multi-factorial aetiology of WMSD [79]. Most of the scientific studies of WMSD report that women are at higher risk than men, regardless of the kind of work or occupation involved [132]. However, there is a discrepancy between the prevalence of WMSD in low back and neck/ upper extremities among men and women; while men are slightly more vulnerable to develop low back, women are more vulnerable in neck and upper extremities [75].

The reasons for these gender differences are not always obvious but the factors such as biological differences in body size, muscle strength and aerobic capacity are suggested to cause the observed differences [75].

Particularly among VDU users in the Swedish workforce, women reported substantial increase in WMSD symptoms [34].

Additionally, every individual may have different working technique (i.e. wrist postures, finger movements, speed/jerkiness of movements, etc) when performing VDU and this has been shown to be influential in developing WMSD symptoms in the field studies [80], higher muscular load has been observed during computer work [133]. Age and anthropometric measures are also among the known individual factors playing a role in WMSD development [117]. In the studies of this thesis, the subjects were mainly picked from male students who had a fair experience of computer work and subject pool was rather homogenous in terms of age and gender as these studies mainly focused on acute response during computer work with normal painful and sores muscle.

Exposure_response_effect model

Exposure-response-effects model descriptively standardises the interaction of aforementioned risk factors and individual differences in the working environment (Fig. 1). This model distinguishes between dependent and independent variables as well as trying to define the framework for pathogenetic mechanism [117, 140].

In this model, external exposure implies the factors such as work organization, work place and work task being independent of the individual performing the task. The transfer of external exposure to the body results in an internal exposure, which refers to muscles, tendons or joints load. Acute response is the instantaneous physiological and psychological reactions of each individual to the internal exposure. The acute responses reflect a number of processes such as muscle fatigue, discomfort, pain, and changes in heart rate, muscle activity, force exertion and movement related to the physical and mental loads. These changes are generally assessed by subjective and objective measures of e.g. rate of perceived exertion, level of discomfort of pain, heart rate, surface electromyography (SEMG), mechanomyography (MMG), force exertion, posture and movement. Chronic effects comprise lasting adaptation to work and WMSD can develop by lack of recovery

after performing the work. As it can be seen in this model, individual factors are affecting on all layers of the model except the external exposure which is independent.

Exposure may be thoroughly expressed based on its three characteristics e.g. level, repetitiveness and duration. Most ergonomic textbooks give a high priority to detailed guiding in how to minimize the exposure level by adjusting the workplace [22, 51]. However, physiological and epidemiological studies suggest that a reduction of workload is not sufficient to prevent disorders [139, 142]. Instead, changes in repetitiveness of the musculoskeletal load are suggested as an appropriate intervention concept [69, 76] especially in those occupational setups where the exposure level is generally low like VDU operators.

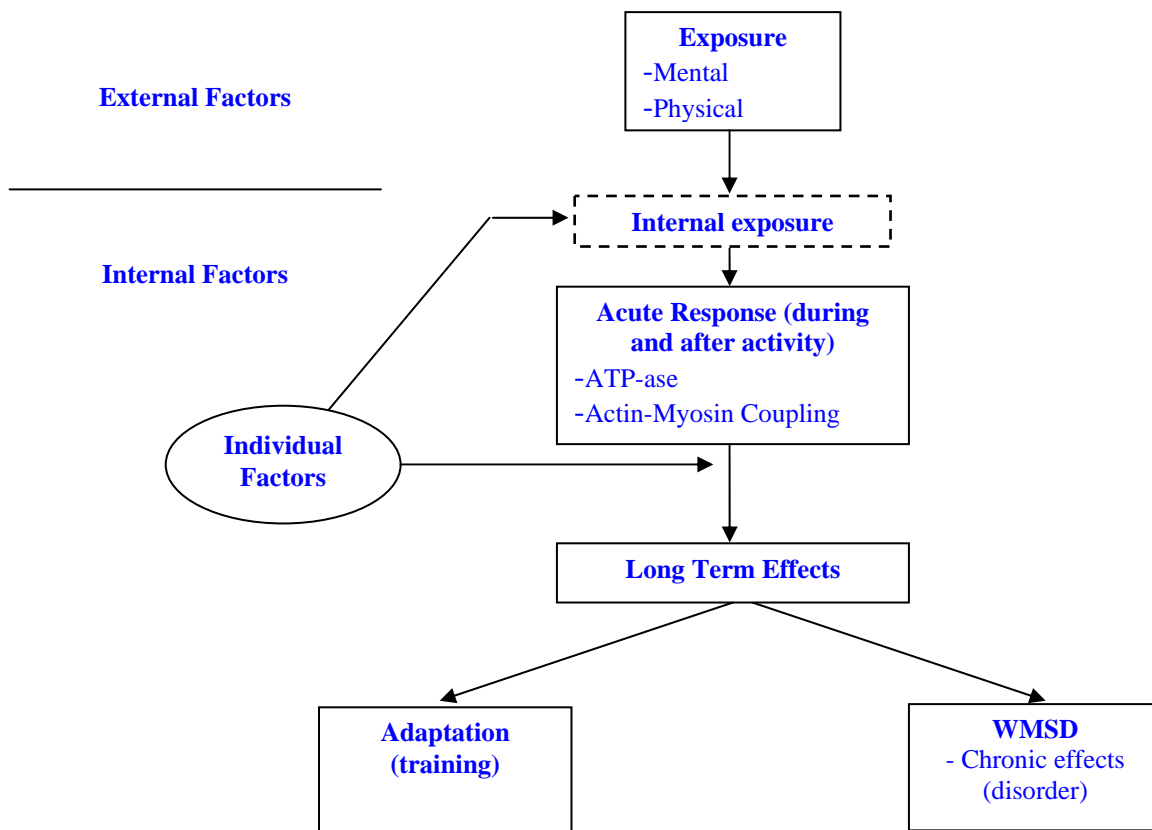


Figure 1: Exposure-response-effects model adapted from [117, 141]

Exposure variation and diversity

Epidemiologic studies strongly suggest that monotonous, static or repetitive physical exposure in jobs is a risk factor contributing to WMSD [10, 19].

In these cases, more “variation” is suggested as a remedy and can be obtained either through organisational measure, e.g. introduction of alternative work tasks, or by utilizing the abundance of the motor system to perform a particular work task in a less stereotyped fashion [93]. Increasing the variability of muscle activity may be achieved in many manners, e.g. through job enlargement, job rotation or increased pause allowance [92].

There are a few methods to quantify the exposure variation and diversity e.g. exposure variation analysis and regularity indices which will be discussed in method section.

Work related pain: Experimental pain models (endogenous, exogenous) and its relevance to work related pain

Pain in deep structures including cartilage, tendons, ligaments, and muscles is one of the most consistent symptoms associated with WMSD in e.g. the upper extremity [83]. Increased muscle load or sustained repetitive muscle activity could result in a higher accumulation of Ca^{2+} and metabolites in the muscles [33, 49, 113], which might be sufficient to activate nociceptors. Recurrent acute pain episodes may induce sensitization and can in turn lead to chronic work-related pain. Another possible complementary mechanism underlying the pain modulated muscular activity is defined via an effect of sympathetic nervous system on muscle fiber contractility which leads to decrease in discharge rate of motor units in the painful muscles when performing the static task [38].

The sensation of acute muscle pain is the result of activation of group III and IV muscle receptors (nociceptors) responding to strong noxious mechanical or chemical stimulation. The muscle nociceptive afferents terminate in laminae I, II and V of the dorsal horn or of the subnucleus caudalis in the brain [96]. Continuous input from nociceptive afferent can trigger the spinal circuits, leading to central sensitization, maintaining a chronic pain state [143].

One way to gain insight into the transduction, transmission, and projection of nociceptive input is to use experimental pain models. Experimental muscle pain models are of great interest because they cause

transitory well-controlled muscle pain that can most likely mimic clinical conditions in some aspects. Experimental muscle pain can be induced endogenously inducing muscle pain by natural stimuli, for example by ischemia or repetitive eccentric loadings at a supra-maximal level causing delayed-onset muscle soreness (DOMS). Experimental muscle pain can also be induced exogenously by external interventions such as electrical stimulations of muscle afferents or intramuscular injection of algogenic substances like hypertonic saline [123].

However, these two pain situations may be etiologically different since the former is related to load exacerbating tissue tolerance leading to rupture and damage of muscle fiber structure and cause DOMS manifested by mechanical muscle hyperalgesia, occasional resting pain, and altered motor control [6, 74, 103]. The latter is probably more related to a change in metabolites and damage of the fiber membrane leading to change in interstitial and intracellular ion balance [83]. The osmotic strength of hypertonic saline most likely shrinks the terminal endings of sensory fibres that may in turn excite nociceptors by opening mechano-sensitive channels or cause the release of other excitatory agents [57].

Different pain mechanism underlying these two methods points out that different outcome could be expected in presence of either of endogenous or exogenous pain model. Investigating the muscular activity response in presence of pain especially during the computer usage will help knowing the features of painful muscle and its interaction with applied intervention.

Intervention procedures

Due to the lack of knowledge on the etiology of WMSD in general, there is to date no effective treatment. Indeed, the prevention of WMSD is still considered as the best treatment [83].

Intervention studies aiming at decreasing WMSD occurrences among the working staff should comprise education and training to teach employees appropriate work practices, muscle control and workstation adjustment. Additionally, administrative controls such as rotation of work tasks or alterations in work rest breaks should be considered [42]. Regardless of adopted intervention approach, the general aim of workplace

intervention is to reduce exposure [23]. However, evaluation of intervention approach has remained inconclusive in a number of studies because of the lack of attention to research design, inadequate reporting of uncontrolled co-intervention and limited analytic adjustment for such co-intervention, poor descriptions of populations exposures, and interventions and inadequate accounting for the timing or impact of interventions [136]. Additionally, the traditional approach of interventional studies to reduce the physical load may not necessarily be beneficial for many modern sedentary occupations [120].

Pauses

Introducing an effective work-rest schedule has been found to be an inexpensive and advantageous approach to reduce WMSD problems associated with VDT personnel [7, 28, 46, 59, 95]. Different work-rest regimes have been tried and their effect on performance and discomfort level has been investigated [17, 77]. However, their suggestion comprises very infrequent pause stages in the working schedule. In line with these findings, the effect of frequent and short rest pauses has been investigated and this regime was shown to be able to increase the productivity [59].

Most of the aforementioned studies introduced pauses as a rest breaks within the working time while passive pauses are not found effective for preventing neck-shoulder pain [18] even though a decrease in pain intensity has been reported among workers with chronic neck-shoulder pain [131]. This finding may be explained by the persistent activity of the upper trapezius muscle during both short and long passive pauses during computer work [13]. Active pauses have been introduced as an alternative or at least as a supplement to passive pauses in some studies [29, 121], [I].

The concept of active pauses is associated with active recovery which is well-known in sports science [8, 134]. Brief increase in the exerted force has been shown to result in motor unit recruitment and de-recruitment in the trapezius muscle [135]. This may prevent overloading of type I muscle fibers mainly involved in low load work e.g. computer work [128]. Additionally, imposed contraction at higher level during a sustained task is increasing the endurance time and contributing to redistribute muscle load [36].

Investigating the acute response of active and passive pause during computer work could give a better insight to define an efficient break regime in working time. Additionally, its interaction in presence of muscle pain and sore muscle and its efficacy to counteract the effect of pain and soreness is worthwhile noting.

Biofeedback

Biofeedback of muscle activity is a recommended method for improving the awareness of insufficient muscle rest during work [9, 107]. Computer users receiving appropriate feedback on their muscle activation learn how to avoid excessive muscular activation [61]. Biofeedback is shown to be effective in decreasing muscle activation level or changing the activity pattern of the descending part of the trapezius [61, 88]. However, biofeedback may not only have positive features as activity increase in other muscle parts or muscles of the shoulder girdle have been reported in response to biofeedback [106, 107]. Thus, biofeedback may just redistribute the load among synergists and lead to a new muscle load pattern that could be detrimental. This calls for assessing other synergistic muscles and in particular other compartments of trapezius or its spatial organization of muscular activation.

To investigate the possible the reorganizational effect of biofeedback system high-density surface electromyography (HD-EMG) was used allowing spatial as well as temporal assessments of EMG changes. Spatial heterogeneity of muscle activity is reported to play a functional role in terms of higher endurance time in trapezius muscles [39, 84]. The importance of reorganizational role of biofeedback calls for design approaches which are able to combine information from multiple locations of muscle activity.

So far, most biofeedback studies have used simple measures (e.g. EMG amplitude and gaps) as source of information for generating feedback [9, 61, 64, 88]. However, these features may not be sufficient to reveal the relevant characteristics of potential risk factors and in turn, face with limitations related to estimation of threshold of “safe working”, i.e. set to a constant absolute [61] or to an individual relative value [88]. This calls for utilizing of new features of the EMG as biofeedback source. As such, the regularity indices of signal have been used to address this query. A new design of biofeedback system was suggested which was built

based on Fuzzy logic concept and could merge multiple uncertain sources of information. This may enable us to solve the aforementioned limitations of conventional biofeedback.

Aims

The current PhD study aimed at incorporating passive/ active pause with applying biofeedback to make a benchmark for new intervention scheme. Additionally, the passive/ active pause effect in presence of muscle pain and soreness was of interest to be investigated.

A new biofeedback design was planned to be designed which could improve the processing capabilities of such system. This attempt proceeded by merging the conventional understanding of proper intervention to reduce the mechanical load beside a novel trend of increasing the irregularity of muscular activity pattern. Finally, as this project enlightens the new perspective of biofeedback design, simultaneously introduce new pitfalls in this advanced technique.

To fulfil the aims five studies were performed where at first three studies pauses were applied on regular basis to reveal the potentially beneficial effect of pause and its interaction with altered proprioceptive condition induced by experimental pain modalities namely hypertonic saline injection (muscle pain) and excessive eccentric exercises to cause delayed onset muscle soreness. Two last studies were performed where the pause time were controlled by the output of newly designed biofeedback system. Figure 2 illustrates the flow of these studies.

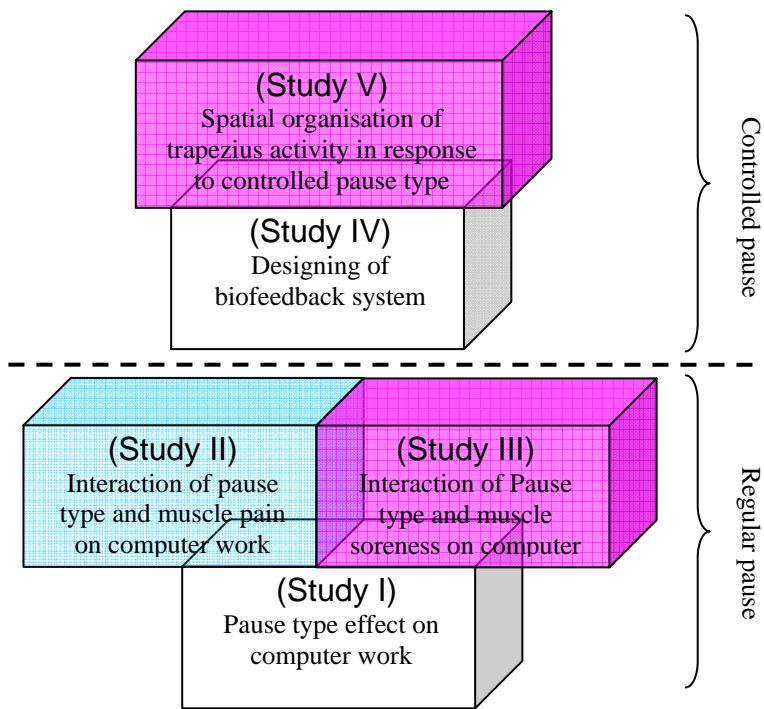


Figure 2 The flow of performed studies

Methods

The study of the interaction between musculoskeletal discomfort, pain and muscular activation has attracted substantial attention. This PhD project includes the results of 5 cross-sectional studies. This chapter presents the subject population, the methods used to assess psycho-physiological measures (discomfort and pain) and to record SEMG activity. The modalities of experimental pain (e.g. injection of algogenic substance and delay onset muscle soreness) which have been used in current studies are also presented. Finally, the chapter briefly reports the conducted analyses and the extracted parameters.

Subjects

In total, 37 healthy (without neck-shoulder disorders) male subjects (35 right and 2 left handed) have volunteered in studies I-V. The volunteers were staff and students at Aalborg University and all of them were experienced with computer use with no history of chronic pain or diseases in the shoulder and neck region.

Table I shows the properties of subject pool for all studies.

Table 1. Subject pool properties in each one of the studies

Subjects	Number	Age	Height	Weight
Study I,II	12	22 (3)	183 (9)	77 (9)
Study III	12	23 (3)	183 (8)	77 (11)
Study IV, V	13	28 (5)	177 (8)	72 (9)

The studies were approved by the local Ethical Committee (N-20070004 MCH), and informed consents were obtained from all participants. The studies were conducted in conformity with the Declaration of Helsinki.

Measurement modalities

Discomfort

Discomfort is expressed in such terms as feeling stiff, strained, cramped, tingly, numb, unsupported, fatigued restless, sore and in pain [78]. Discomfort measures may reflect an early perception of pain related to the

biomechanical load applied to the musculoskeletal system [108]. To evaluate discomfort, visual analogue scale (VAS) was used. A VAS is a horizontal or vertical line anchored at each end with description of the extremes (“0: no discomfort” and “10: maximum discomfort”) of the investigated subjective sensation. Subjects can rather easily describe feeling of discomfort [78]. In the current thesis, the subjects were asked to score discomfort sensation in the shoulder/neck region.

Pain intensity

Pain intensity in (II) was assessed continuously with a VAS (Aalborg University, Aalborg, Denmark). The VAS was anchored with “0: no pain” and “10: intolerable pain or most pain imaginable”. Experimental muscle pain was induced by i.m. injections of sterile hypertonic saline (5.8%) injected over 15 s in healthy subjects using a 27Gx1-1/2” cannula. The injection point was 2-cm lateral to the halfway point between the spinous process of the seventh cervical vertebra (C7) and the lateral edge of the acromion. Saline mostly spreads along the muscle fibre direction and minimally in the transversal direction [53], thus after the bolus injection it was mostly concentrated along the C7-acromion line. The pain intensity following intra-muscular injection of a bolus of hypertonic saline lasts for approximately 5 min [90, 91]. Subjects were regularly reminded (approximately every 10 s) to report changes in pain intensity.

Eccentric exercise was performed to induce DOMS which could cause muscle soreness and consisted of 50 contractions where the subjects resisted the dynamometer moving from the subject’s maximum to minimum shoulder position at a force equal to 100% maximum voluntary contraction. The contractions had no time restrictions, and the subjects were verbally encouraged during the exercise. After 10 contractions (equivalent to 1 bout), the subjects relaxed for 2 min.

Surface electromyography (SEMG)

The SEMG signal represents the current generated by the ionic flow called action potential across the membrane of muscle fibres propagating through tissues to reach the detection surface of electrodes placed

above the active muscle [30]. Two different modalities of surface EMG were used to assess the muscular activity and in turn physical exposure in terms of muscle load.

Conventional bipolar EMG

Bipolar surface electrodes (Ambu A/S, Neuroline 720 01-K/12, Ballerup, Denmark) were aligned with an inter-electrodes distance of 2 cm on abraded ethanol-cleaned skin along the direction of the muscle fibres. Electrodes were placed: (i) On the main superior muscle bulk ~ 20% lateral to the midpoint between the cervical spine (C4) and posterior lateral third of the clavicle for the uppermost (clavicular) part, (ii) ~20% medial to the midpoint between the acromion and the C7 vertebra for the second upper (descending) part, in studies IV and V this position recorded on the contra lateral side as well, (iii) ~20% medial to the midpoint between the medial border of the scapula and the T3 vertebra for the uppermost lower (transverse) subdivision, this position was not recorded in studies IV and V and, (iv) ~33% medial to the midpoint between the medial scapular and the T8 vertebra for the lowest (ascending) subdivision [63]. The reference electrode was placed on the C7 vertebra. SEMG signals were amplified 2000 times, and band pass filtered (5-1000 Hz). SEMG signals were digitally band-pass filtered (Butterworth, 4th order, 10-1000 Hz). Furthermore, a notch filter (4th order Butterworth band stop with rejection width 1 Hz centred at four first harmonics of the power line frequency) was used when necessary to remove line interference.

High density EMG (HD-EMG)

In contrast to conventional bipolar EMG which only gives the temporal information on muscular activity, this technique allows grasping spatial as well as temporal assessments of EMG changes and investigates any possible functional reorganization of muscular activity in response to biofeedback. HD-EMG signals were detected with a semi-disposable adhesive grid of 64 electrodes (LISiN-Spes Medica, Italy, model ELSCH064). The grid consists of 13 rows and 5 columns of electrodes (2-mm diameter, 8-mm inter-electrode distance in both directions) with a missing electrode at the upper right corner serving as the origin of the coordinate system to define electrode location (Figure 3).

The silver–silver chloride electrode surfaces in the grid are separated from the skin by a small cavity (~1-mm

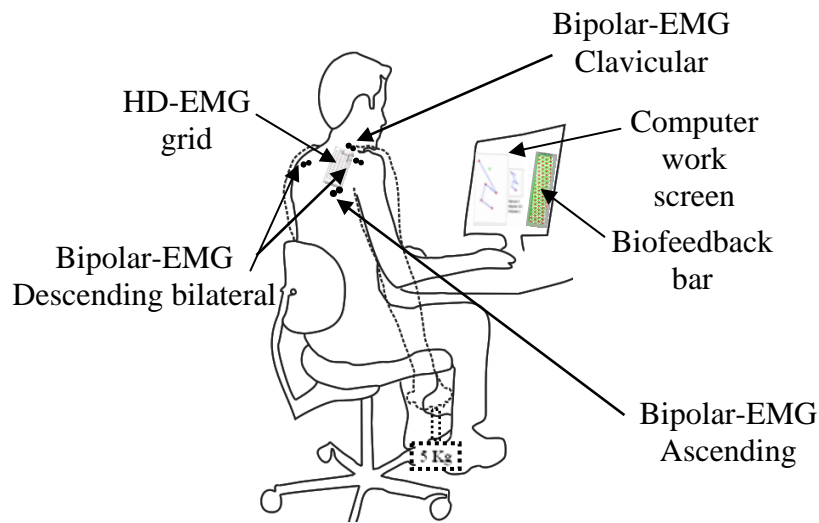


Figure 3 Measurement setup and body posture in studies IV and V

thick) filled with electrolyte gel. The EMG signals were bipolarly amplified 5000 times (128-channel surface EMG amplifier, SEA64, LISiN-OT Bioelectronica, Torino, Italy; 3-dB bandwidth, 10– 500 Hz), sampled at 2048 Hz, and A/D converted in 12 bits.

Before placement of the grid, the main innervation zone of the upper trapezius muscle along the C7-acromion line was identified in a few test contractions with a linear array of 16 electrodes (silver bars, 5-mm long, 1-mm diameter, 5-mm inter-electrode distance) [40]. The 64-electrode grid was then placed on the upper trapezius muscle with the 4th row aligned with the C7-acromion line, parallel to the muscle fiber direction. The lateral edge of the grid was 10 mm medial to the identified innervation zone. The reference was placed at the same position as that of conventional bipolar EMG.

Figure 3 illustrate the measurement setup including conventional bipolar electrode positions with respect to HD-EMG grid on clavicular and bilateral descending and ascending parts of trapezius, body posture during computer work depicting active pauses/reference contraction (dashed lines). Note on the computer screen, mouse work drawing and biofeedback bar. This setup was utilized in studies IV and V.

Analysis and development methods

This section gives a summary of all processing techniques used in this PhD project and particularly explains the basis of the Fuzzy inference system developed and utilized in study IV and V. In ergonomics similar to the other fields of science which deal with EMG, the raw data is converted to some relevant parameters which preserve the temporal profile of variation (mainly global features of EMG in ergonomics) and then further data reduction is performed to interpret the data. For each processing tool, a commentary explaining the technical pitfalls and limitation of the methods is provided.

Root mean square (RMS) and relative rest time (RRT)

The SEMG signal is considered to be a non-stationary stochastic process and can be estimated by its probability function, i.e. mean and variance. The mean of the SEMG can be estimated to be zero while its variance is given by computing root mean square (RMS) values. RMS is likely to be preferred to average rectified values as RMS measures the amplitude or energy of the signal [30]. The amplitude feature of EMG, like RMS shows a monotonic, sometimes linear relationship to the generated force in the muscle [98]. However, the EMG amplitude can also be affected by muscle fatigue and increase [99]. Beside physiological reasons, EMG amplitude changes may also be due to numerous confounding variables e.g. anatomical properties of muscle, crosstalk, electrode location and muscle length.

Another amplitude index of EMG called RRT, has been shown to be more robust against the electrode dislocation and to have lower intra-subject variability [60]. RRT is defined as the percentage of time in which root mean square (RMS) was below a threshold for at least 250 ms.

A few studies chose a constant threshold (6 μ V) which is above the RMS level of the recording chain on non-active muscle [60] while some others suggested a normalized threshold with respect to a reference task [58, 127].

However, setting a constant threshold is probably a good idea to design an ambulatory biofeedback system but it may not be a good idea if there is no such technical limitation especially if the subject pool is not

homogenous because the thickness of subcutaneous layer may affect on EMG level [104]. On the other hand, normalization to a reference task can also introduce some variability terms [67]. To set this threshold, in the studies of current PhD project, a heuristic method adopted where based on the SEMG signals recorded during the instructed rest, the threshold was adjusted with increase or decrease in 5% step of an arbitrary initial threshold (6 μ V) until RRT in the rest period was at least 99%. However, it is also conceivable that this method relies on the ability of the subjects to relax their muscle, and sensitive to the noise level in SEMG recordings.

Additionally, for tasks performed at low load levels, RRT will change very widely [58]. This wide range of variation restrains the monotonic range of RRT with respect to activation level. Due to this limited monotonic range, the usage of such index as a source of biofeedback is rather difficult even though it has been used in couple of studies [61, 130].

Another issue about EMG amplitude indices (e.g. RMS, RRT) is that they may be sensitive to some artefacts in presence of experimental pain for example, possible effect of intramuscular bolus injection on the skin-electrode impedance. To our knowledge, there is no study addressing this issue, but it is conceivable that hypertonic saline may decrease the impedance between two electrodes. In the current project, the impedance before and after the experiment was checked and no significant changes were found.

Additionally, heart activity can considerably affect on EMG recording on upper extremities [58, 101], however, increasing the low cut off frequency of the band pass filter to 30 Hz, which will remove the main contributed signal energy due to heart activity artefact [58] did not considerably change the results. It is arguable that this method may also remove some part of EMG information but this issue has been under focus of some recent studies to remove this artefact more elaborately [32, 145].

Exposure variation analysis (EVA)

EVA is a method to reduce the information of exposure pattern into a data-sheet according to exposure level and repetitiveness. It was first introduced by [94] and represents the exposure pattern in three dimensions e.g.

level, repetitiveness and duration. The outcome of an EVA analysis is a three dimensional plot whose third axis represent the percentage of time that exposure level remains at a particular level and time class.

The level and time classes are defined based on a logarithmic lay-out because the accommodation of physiological responses to a change in exposure level is rapid immediately after a change and levels off gradually with time [94]. However, set-up of these classes is a matter of compromise between a too coarse data reduction (few classes) and an undue dilution of data (many classes). This suggests the concern about the optimality of EVA which is one of the main issues in utilizing such method.

Regularity indices

Statistical measures of time-series variability (i.e. standard deviation, coefficient of variation, etc) are often used to quantify the size of motor variability [85, 93] due to their simplicity. However, these methods do not provide any information of the occurrence of recurrent patterns through the same exposure pattern [21, 119].

Despite this shortcoming in exposure variation analysis, methods are available in advanced signal analysis for quantifying degree of complexity (in nonlinear analysis), regularity and self-similarity of exposure pattern, which may provide an insight into this issue [109].

Regularity can be defined as the tendency towards recurrent patterns through a time-series of the investigated signal. Kolmogorov-Sinai entropy has been defined to quantify regularity and using a straightforward formula posed by Grassberger and Procaccia [52]. However, there are two paramount issues in applying this formula to experimental data. The amount of data needed to get accurate entropy estimation and the effect of noise causing serious discontinuity in the estimated entropy values. Actually, even small quantity of white noise regardless of signal to noise ratio will lead to estimated entropy tending to infinity [109].

Sample entropy (SaEn) can potentially distinguish low dimensional deterministic systems, periodic and multiply periodic systems, high-"dimensional" chaotic systems, stochastic, and mixed systems [112]. Although SaEn is defined to deal with short time series (approx. 1000 samples), it is from a computational

point demanding and is not possible to implement in some online applications. Permuted sample entropy (PeSaEn) was introduced in this PhD project and showed to be a fair estimate of SaEn [114].

As such, irregularity in motor unit/muscle activation may be beneficial in term of fatigue reduction and, eventually, health, since it may counteract continuous activation of small type I fibers, which has been proposed to occur during “static” work and lead to muscle injury [56, 116, 128]. Beside that, increased entropy, as a measure of irregularity, reflects the adaptability of biological systems so healthy systems are expected to have higher values of entropy than unhealthy systems [26]. Entropy has also been used in relation to back pain and could recognize healthy subjects from patient group whereas conventional frequency analysis failed [122].

To study the spatial heterogeneity of muscle activation, image entropy was estimated for absolute/normalized RMS maps extracted from HD-EMG recordings. Image entropy is a statistical measure of randomness (heterogeneity) and can be used to characterize the texture of the image. Entropy is defined as $\sum p \log(p)$ where p contains the histogram counts in each bin divided by the total number of channels in the map [50]. It should be noted that although the theoretical background of entropy estimation, either PeSaEn or image entropy, are close but image entropy quantifies the irregularity of an image which in this case is the image given by RMS maps extracted from HD-EMG and reveals the spatial irregularity of muscular activation over upper trapezius and partly middle part of it. On the other hand, PeSaEn quantifies the irregularity of EMG time-series and how this irregularity evolves in time and no spatial information is revealed by this index.

Fuzzy logic and inference and its role in designed biofeedback system

Fuzzy logic is a method of rule-based decision-making used for expert systems and process control that emulates the rule-of-thumb similar to those that human beings use. Traditional Boolean set theory is two-valued in the sense that a member either belongs to a set or does not, which is represented by a one or zero,

respectively. Fuzzy set theory allows for partial membership, or a degree of membership, which might be any value along the continuum of zero to one.

The primary building block of fuzzy logic systems is the linguistic attribute. A linguistic attribute is used to combine multiple subjective categories describing the same context. For instance in the current designed feedback system, “HIGH”, “MEDIUM” and “LOW” are linguistic attributes of RMS that specify the uncertain and subjective category of EMG amplitude. Another basic fuzzy logic concept involves rule-based decision-making processes. These rules can be set out such as IF <situation> THEN <action>.

The fuzzy inference took four inputs comprised of RMS and PeSaEn of ipsi-lateral clavicular and descending called as entries. For each entry, three fuzzy linguistic attributes (“LOW”, “MEDIUM” and “HIGH”) were defined. A full combination of 4 entries with 3 attributes gives 81 fuzzy rules where all have similar form. The consequent (Feedback strength in table 2) was basically defined using the existing knowledge about physical risk factors (briefly discussed in the introduction section) during computer work. As such, low PeSaEn and high normalized RMS should increase the likelihood of applied feedback meaning that in those cases the consequence should set to “HIGH” or vice versa.

However, some of the rules were not in line with our hypotheses (i.e. lower PeSaEn and higher RMS as risk factors) where two entries of a single EMG channel contradicted each other (measure contradiction) and/or the attributes from descending and clavicular parts contradicting each other (channel contradiction). Channel contradiction incorporates to cases where PeSaEn or normalized RMS are seen as “HIGH” in one of the channels (clavicular/descending) while they are seen as “LOW” in the other one or vice versa. Measure contradiction incorporates cases where PeSaEn in one of the channels is seen “HIGH” while normalized RMS is also “HIGH” or vice versa. In such cases, the rules were down weighed by halving the rule weight per respective contradiction and setting the consequent to “MEDIUM”. If the contradiction occurs while one of the entries is seen “MEDIUM” instead of halving the rule weight it was multiplied by 0.75. Table 2 shows some examples of such fuzzy rules and illustrates channel/ measure contradiction.

Table 2. Examples of fuzzy rules adopted in biofeedback system

Clavicular		Descending		Feedback strength	Rule weight
PeSaEn	RMS	PeSaEn	RMS		
LOW	HIGH	LOW	HIGH	HIGH	1
HIGH	LOW	HIGH	LOW	LOW	1
LOW	LOW	HIGH	LOW	MEDIUM	0.25

The membership functions were defined symmetric and they were specified by some parameters with imposed configuration. During computer work, triggered rules were probed and if the triggered attributes of each one of the entries were continuously the same e. g. “HIGH” more than an arbitrary time limit (40 seconds) the parameters of membership function of that particular input was readjusted based on history of collected values from that particular entry.

The rules combined into a single fuzzy set using “Maximum” operator (Fuzzy OR) to perform the aggregation step of fuzzy inference. Finally, defuzzification was performed computing centre of area under the aggregated fuzzy membership function. Figure 4 illustrates a typical mamdani fuzzy inference system implementing the fuzzy rules corresponding to the rules denoted in table 2.

If the output of fuzzy inference exceeded 0.7 as the rising point of “HIGH” attribute the feedback alarm could potentially set to “on”. During the first minute of recording, the feedback was set to silent to prevent applying feedback due to possible transient effect and re-adjustment of Fuzzy membership functions. Fuzzy inference was also blocked from generation of two successive alarms with a time interval less than 30 sec as an accumulative fatiguing effect was found in our previous studies when the time interval between two successive active pauses is below this limit [II].

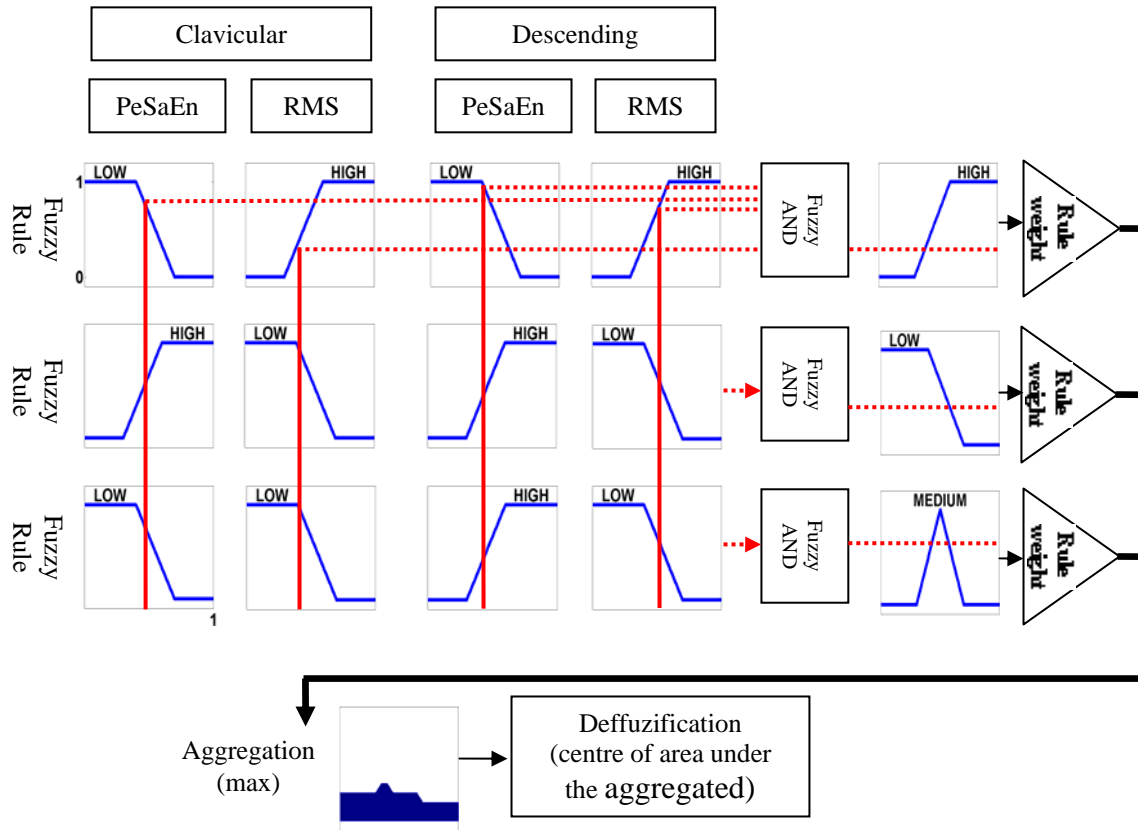


Figure 4. Structure of fuzzy biofeedback inference system

Studies specification

Five studies of current dissertation differed in terms of adopted methodological modalities and signal processing approaches. Table 3 summarize these properties. It should be noted that studies IV and V were performed simultaneously but study IV mainly focus on technical details of biofeedback system design whereas study V mainly focus on some physiological discussion of the findings and particularly the results of HD-EMG recordings.

Table 3. Specifications of performed studies in current PhD framework

	Study specification	Study I	Study II	Study III	Study IV	Study V
Pause control	Regular based					
	Biofeedback based					
Experimental pain	Hyper tonic injction (pain)					
	Delay onset muslce soreness					
EMG recording on trapezius	Clavicular					
	Descensding					
	Transverse					
	Ascending					
	Descending contra-lateral					
	high density					
EMG analysis	RMS					
	RRT					
	EVA					
	PeSaEn					
	Image entropy					
Other measurements	pain intensity					
	discomfort					

Discussion

The results of current PhD study comprise the intervention procedure including superimposed active/ passive pauses and an advanced biofeedback designed and implemented to control the timing the applied pauses during computer work. The interaction of superimposed pauses with muscle pain and soreness compose the other part of the results. As it was introduced in the first chapter of current dissertation, several factor could influence on muscle activity but in order to decrease the confounding factors the subjects were instructed to follow the ergonomics guideline for a proper posture in office work (i.e. sit and desk height, shoulder abduction, etc) [78].

Effect of active/ passive pause on muscle activity during computer work

As passive pauses of quite long durations are shown inappropriate to generate complete rest of the upper trapezius muscle during computer work [13], it is crucial to look for new alternatives. In this PhD project, very short regular burst of static contractions in the shoulder region (shoulder shrug about 30% MVC) were investigated. They resulted in a shift of EVA centroid towards lower values compared with passive pause for trapezius EMG [I]. It means that active pauses can increase the variability of the trapezius activity during a standardized computer task. This can be considered as a positive effect because changing the activity pattern during monotonous work tasks may be a well-suited intervention strategy for preventing WMSD [85, 86, 93]. Positive effect of short periods of increased contraction levels during sustained contractions in reducing fatigue development of the upper trapezius has formerly reported [36], however, this PhD project aimed at utilizing this finding in a practical fields. The positive effect of voluntary contractions during pauses could be due to improved local muscle circulation. This is supported by the observed trend for increased muscle oxygenation following active pauses [28].

Additionally, active pause contributed to induce higher spatial irregularity and changes in activity pattern of trapezius [V]. This was represented by higher spatial irregularity of RMS and a caudle shift of centre of gravity of RRT extracted from HD-EMG maps. Higher spatial irregularity may imply more heterogeneous coordination between different compartments of trapezius since the area covered by the electrode grid represented the upper and partly middle trapezius. In contrast, active pause may increase the regularity within a muscle subdivision shown with lower PeSaEn (studies IV and V). Concomitantly, more irregular activation pattern of the ascending part of the trapezius was found, which could be positive trend as higher irregularity is suggested to be associated with healthier functionality of physiological system [26].

The association of higher spatial irregularity and caudle shift in RRT maps is line with [39]. The observed changes in the spatial pattern of activity of the muscle may be due to spatially inhomogeneous changes in motor unit discharge rates or in motor unit recruitment/derecruitment [135, 138]. This may highlight a reorganization of the muscle in response to active pause.

Timing for applying such pause e.g active pause is a crucial issue. An increase in EMG amplitude in the trapezius was found when pauses were applied in shorter intervals (40 s) [II, III]. Similar effect of active pause was observed on contra-lateral descending part of trapezius part [IV,V]. Apparently, there is an accumulated fatiguing effect following frequent pauses, and this increase in amplitude may be due to this phenomena.

Another issue which remains to be investigated is the type of applied pauses. In current PhD project, static contraction introduced as active pause but it is conceivable that other types of active pauses (e.g. dynamic active pauses of shoulder elevation or abduction) could have different outcomes. It should also be noted that contribution of active pause towards making more variable pattern of activity does not necessarily mean that it can also contribute to more irregular activity of trapezius muscle represented by higher PeSaEn values. In studies IV and V, active pauses contributed to lower irregularity. Adopting different types of active pauses may lead to different results in terms of variability and regularity.

Active pause can also promote bilateral changes in the trapezius muscle activity pattern most likely highlighting recruitment/derecruitment of active low threshold motor units. Bilateral modulation of the trapezius activity is probably due to the close neural connections and bilateral activation of the homologous trapezius muscles [4]. Holtermann and co-workers [64] also showed modulation of EMG amplitude in the contra-lateral trapezius due to applied biofeedback to decrease muscle activity.

The main findings of current studies concerning pause types was that active pauses can contribute to induce a more variable and more irregular spatial organisation of muscle activity over upper and part of middle trapezius during computer work but irregularity of muscle activity pattern can decrease the irregularity within a one compartment of trapezius.

Effect of experimental pain on muscle activity during computer work

Both types of applied experimental pain e.g. exogenous and endogenous resulted in degrading the potentially beneficial effect of active pause. The shift of EVA centroid of trapezius EMG along the time scale towards lower values was no longer significant in presence of acute pain induced by injection of hypertonic saline or DOMS. However, there is a minor discrepancy between the control sessions of two studies, while the active pause contributed to shift the EVA centroid toward lower values in all recorded parts of trapezius in [II], this can only be seen in the clavicular part of trapezius in [III]. This might have been due to lack of optimality of EVA which was discussed in the method section. Figure 5 shows the deteriorated effect of active pause in presence of muscle pain.

The most considerable difference between these two experimental pain modalities was the contribution of acute pain to induce a functional reorganization of muscle activity represented by increase muscular activity in transverse and ascending parts of trapezius. Discrepancies between two modalities of experimental pain could be due to different mechanism underlying the muscle pain. While intramuscular injection with algogenic substances, including hypertonic saline, preferentially activate group III and IV muscle afferents and rarely activate muscle spindle receptors [97], a decreased neural activation following eccentric work is

likely to evoke changes in γ -motor neurone excitability and, in turn, in muscle spindle afferent sensitivity [47]. This will most likely change motor control strategy in presence of muscle soreness [35]. Beside that, DOMS does not usually induce any pain at muscle resting. However, it can induce hyperalgesia [118].

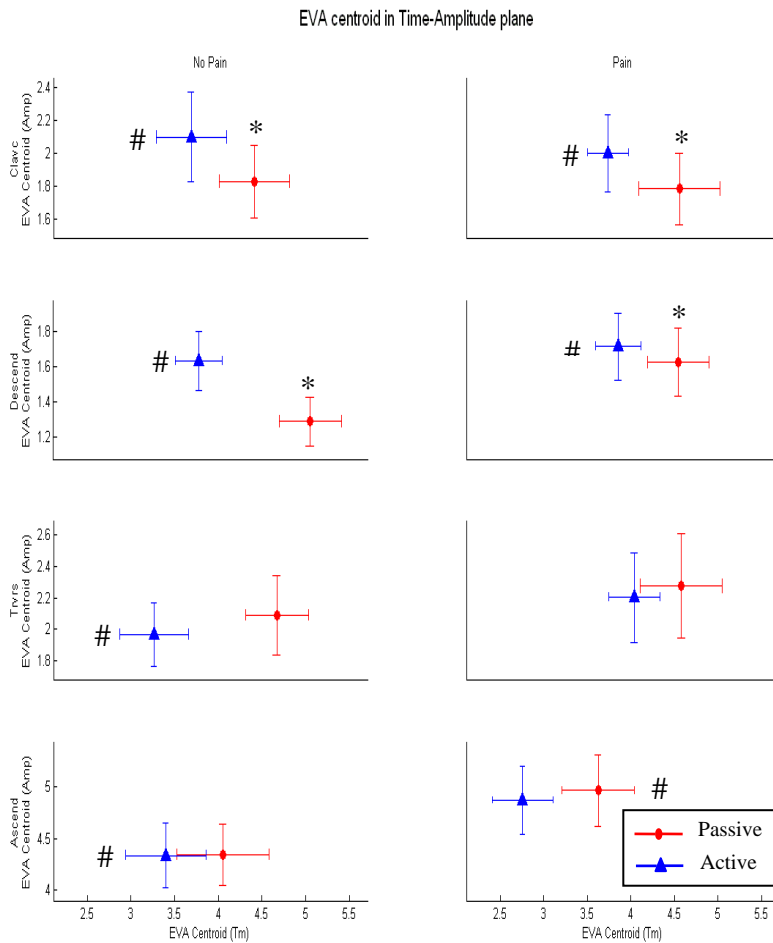


Figure 5. Mean \pm SE exposure variation analysis (EVA) centroid in time-amplitude levels plane in time (horizontal segment) and amplitude (vertical segment) comparing the effects of experimental muscle pain and pause type (active: diamond and passive: circle) for the clavicular (Clavc), descending (Descend), transverse (Trvrs) and ascending (Ascend) parts of the trapezius muscle . * $p < 0.05$ along amplitude domain and # $p < 0.05$ along time domain

The functional reorganisation of muscle activity is in line with [37] who reported similar EMG amplitude increase in ascending part of trapezius with a decreased activity for the descending part during repetitive movements in presence of acute pain. Similar spatial changes in surface EMG activity of trapezius during

sustained contraction were demonstrated which might imply the role of inhibitory reflex mechanisms to move the muscular activity toward the middle part of trapezius [87].

Such functional reorganisation of muscle activity may indicate an ability of the motor system to recruit synergistic muscles, e.g. the lower trapezius assists in rotation of the scapula mainly carried out by the upper trapezius [66]. However, it may also be detrimental in case of recurrent pain as it contributes to increase the load to other parts of the same muscle and/or other muscles and could explain the spreading of pain seen in clinical conditions [91].

The pain adaptation model predicts a decreased EMG activity of the agonist muscle concomitant with increased EMG activity of the antagonist muscle during muscle pain [81], however, at low contraction levels these changes are not always found [11, 89]. More specifically during computer work, a decrease in EMG amplitude of extensor carpi radialis due to acute pain has been reported with low precision while no modulation of EMG occurs with high precision demand [12].

No significant decrease in EMG of descending and clavicular parts of trapezius at the site of injection was found in response to acute pain. This finding may point towards a lack of protective response in the painful region during computer work [81]. However, discrepancies between experimental and clinical pain should be acknowledged as experimental pain induced by intramuscular bolus is the short duration which restricts computer work to only two min sessions.

A decrease in EMG amplitude immediately after eccentric exercise was observed [III]. Similar EMG amplitude modulation during static and dynamic contraction (abduction and shrug) in response to eccentric exercises of the shoulder girdle is previously reported [74, 103]. However, during rhythmic movement (elbow extension/ flexion), both increasing EMG amplitude and non-significant changes were reported [15, 16, 82]. The discrepancies among these results can most likely be due to different levels of muscle fatigue in response to eccentric contractions, type of exercise or task (muscle acting as prime mover or having a postural role like in the present study) and task attributes (e.g. mental load).

The decrease in muscular activity following eccentric exercise may imply a protective mechanism for the contractile elements not to be further damaged. Alternatively, it may imply a shift of load to the other synergistic muscles as an adaptation mechanism [90].

DOMS occurs at 24–48 h after performing the exercises and swelling, loss of range of movement and muscle power [102]. However, in the current PhD project, measurement 48 h after exercise was not reiterated as no changes in trapezius EMG activity between 24 h and 48 h after exercises have been reported [74, 103].

In summary, the potent effect of active pause to induce more variable pattern of muscle activity in trapezius during computer work was deteriorated in presence of both experimental pain modalities namely hypertonic injection and DOMS suggesting a decreased ability to modulate muscle activity pattern in presence of experimental pain and/ or soreness [IV, V].

Biofeedback system design

Fuzzy systems have been extensively used due to e.g. high reliability, low rate of false alarm [105], and tolerance of imprecise data [115]. It can always be argued that the heuristic search for fuzzy rules does not guarantee a useful controller, and that the whole system may not always be stable from a control theory point of view [100]. The main challenges of fuzzy design are defining the proper membership functions and set of rules and in this particular application; it is a bit more of a usual challenge. While most of studies utilizing a biofeedback system regard high EMG activity as a risk factor [61, 88], it has also been reported that a high activity level can contribute to facilitation of electrolyte and fluid balance, improving blood circulation and thus, preventing blood pooling for muscular tissues [29]. This uncertainty on hypothetical risk factors makes it difficult to use recommended approaches to extract fuzzy rules [3] from numerical data.

To overcome this problem, the membership functions of fuzzy biofeedback were readjusted over time. The prototype configuration of membership functions (typical triangular and trapezoidal shape membership functions with imposed symmetry) were fixed and only the parameters were readjusted based on the history of collected data.

This readjustment was not performed in a shorter interval than membership function readjustment interval (MfRI) with respect to previous readjustment. MfRI was set to 40 s in the current design based on some pilots studies. Setting MfRI too high will cause stopping the feedback system not to generate any alarm at all for some cases. This was also shown in offline simulating the biofeedback system for control session and counting the number of feedbacks which would be otherwise applied (virtual feedback). The fact that membership function readjustment did not differ significantly in response to the feedback instruction type may indicate that the type of applied pauses was not efficient enough to enhance the muscular activity pattern.

The strategy of design in this study sounds promising for further studies to develop more advanced and efficient biofeedback design which could eventually be integrated with real working environment.

Conclusions

Active pause resulted in more variable pattern of muscular activity in trapezius which is suggested to be a potentially beneficial effect preventing sustained monotonous activity of motor units. However, this beneficial effect could be compromised in presence of muscle pain or soreness. Additionally, excessive number of active pause may lead to cumulative fatiguing effect resulting in increased EMG amplitude. Biofeedback system was developed to decide about the appropriate timing between successive active pause. This system could merge multiple source of information and features of muscular activity under a fuzzy based decision making core which resulted in higher irregularity over trapezius as a whole although lower regularity was observed in descending part of trapezius. The implemented biofeedback system made a benchmark for further studies on prevention of WMSD.

Perspectives

The type of mouse work in the present laboratory study intended to simulate major features of computer mouse work e.g. repetitions of mouse click in a quasi static posture. This is a simplification of real work, as

factors such as work organization, incentive system and work place physical factors influencing muscle activity are not taken into consideration [85]. Additionally, the sample population is not representative of workers suffering from WMSDs (i.e. mostly females). Therefore, the present results ought to be carefully interpreted before implementation in occupational settings. Further studies including longer duration of computer work and introducing for instance dynamic active pauses instead of static ones are most likely required to delineate effects of active pauses in true occupational settings.

Additionally, a prospective (follow-up) study is required to assess long-term effects of a biofeedback system to decrease the likelihood of WMSD development. Such study has been performed to assess the muscle learning therapy intervention scheme for electronics manufacturer [42]. Positive effect of this scheme in course of 6 to 32 weeks was found which showed a reduction in muscle tension particularly in trapezius.

Ultimately, for being applied in occupational daily settings, the biofeedback system should be easy to use without complicating daily tasks. Use of a type of garment incorporated with EMG dry electrodes have been suggested in some studies [61, 130]. However, this approach did not show a tangible result among asymptomatic subjects [130].

Recently, wearable medical devices have been developed for ambulatory monitoring which could be utilized to integrate the feedback system in working environment [31]. Integrating such system in the working environment give the possibility to investigate the learning effect of such system and evaluate the usefulness of the whole system.

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