Nowadays, monotonous activities involving repetitive hand and finger movements at low force levels are increasingly common in the industrialized world. Exposure to low-force occupational work with prolonged sustained contractions of the muscle might lead to fatigue. Assuming that muscle fatigue is a precursor of upper extremity disorders and may reduce performance of employees, it is important to get an improved insight in temporal patterns of loading during these tasks.

The main objective of this thesis was to assess how EMG manifestations of muscle fatigue develop during low-force occupational work. This thesis describes how EMG indicators of muscle fatigue relate to feelings of perceived fatigue. The relationship between manifestations of muscle fatigue, kinematics and performance was investigated and the effects of temporal aspects of the work (work duration, rest breaks and work pace) on the development of muscle fatigue in the neck and shoulder were established.

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Fatigue and performance in repetitive industrial work

Tim Bosch

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VRIJE UNIVERSITEIT

Fatigue and performance in repetitive industrial work

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad Doctor aan
de Vrije Universiteit Amsterdam,
op gezag van de rector magnificus
prof.dr. L.M. Bouter,
in het openbaar te verdedigen
ten overstaan van de promotiecommissie
van de faculteit der Bewegingswetenschappen
op vrijdag 17 juni 2011 om 11.45 uur
in de aula van de universiteit,
De Boelelaan 1105

door

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geboren te Warmenhuizen

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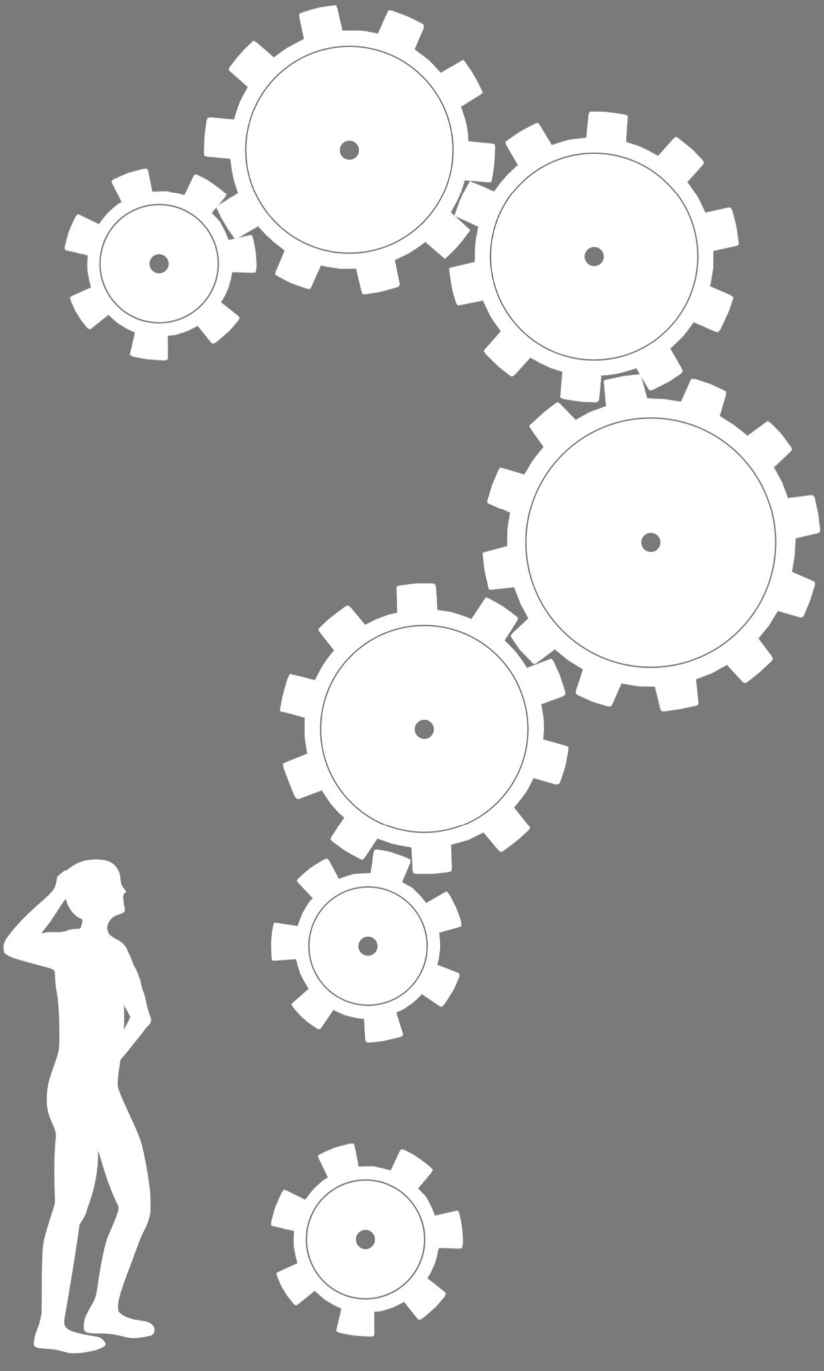
copromotor:	dr. B. Visser

Contents

Chapter 1

General introduction



Prolonged sustained low-force work

In 1973 Walter Rohmert suggested that muscular work starts to become fatiguing at forces exceeding 15 percent of the maximum force (Rohmert 1973). However, fatigue and fatigue related changes have been shown to occur at much lower force levels. In addition, nowadays many health and safety authorities acknowledge that risks for neck and shoulder problems not only arise from jobs with high physical load (exceeding 15 percent of the maximum force) but also from repetitive low-force work with low variation (e.g. Straker and Mathiassen 2009). In the literature, the terms low-force contractions and low-intensity work are both used to indicate the same type of work, namely activities with average muscle activity levels between 5 to 20 percent of the maximum capacity. Low-force and low-intensity are, therefore, interchangeably used in this thesis. Light manual assembly work (Figure 1-1) and office work are examples of such low-intensity activities. These activities are usually characterized by high repetitiveness of movements. Repetitive hand or arm movements are now a feature of work for more Europeans than 10 years ago (Eurofound 2010). More than 60% of the working population currently reports to perform repetitive hand or arm movements at work.

Figure 1-1. *Workers on an assembly line (left) at the Ford Motor Company's in 1913 (AP Photo/Ford Motor Company) and shaver assembly in the 21st century at Philips Domestic Appliance and Personal Care (right). Both are typical examples of short cycle low-intensity work.*

A number of recent trends that can be observed in the industrialized world may further increase the occurrence of tasks which are characterized by low-intensity, repetitiveness and low variability. Since the 1990s, many companies in developed countries have outsourced or subcontracted their routine production activities to low-cost suppliers in the newly industrializing countries (e.g. Volberda et al. 2007). These companies rationalize the remaining core production towards a larger reliance on automation and information technology (Docherty et al. 2002). The increase in automation may have different effects on job design. In industry and logistics as well as in the service sector, an increased implementation of Tayloristic and lean production principles with a strong focus on avoiding time losses can be observed (Womack et al. 2007). A clear example of this can be found in the warehousing sector, where new systems have been introduced accounting for the transport of goods to specific picking locations. Because of these ‘goods-to-man systems’, the travel distances of order pickers within the warehouse have drastically been reduced. Instead of moving into the warehouse to pick products out of racks or shelves, operators work at specifically designed stationary workstations handling high production volumes. This clearly results in more repetitive movements and less exposure diversity. This implies fewer opportunities for variation and recovery through discretionary breaks and a larger occurrence of short-cycle, repeated operations of low-intensity (Mathiassen 2006).

Model

Muscle activity, during work or leisure activities, is generally considered as health promoting. However, prolonged sustained contractions of the muscle with insufficient recovery might lead to fatigue and as a consequence of that to reduced performance. In figure 1-2 a simple model describing the relationship between exposure (e.g. work requirements), acute responses (e.g. muscle fatigue, motor behaviour), long-term responses (e.g. disorders) and effect modifiers (e.g. individual and psychosocial factors) is presented. The acute responses as well as the long term responses may affect performance. Vice versa the level of performance may affect these responses.

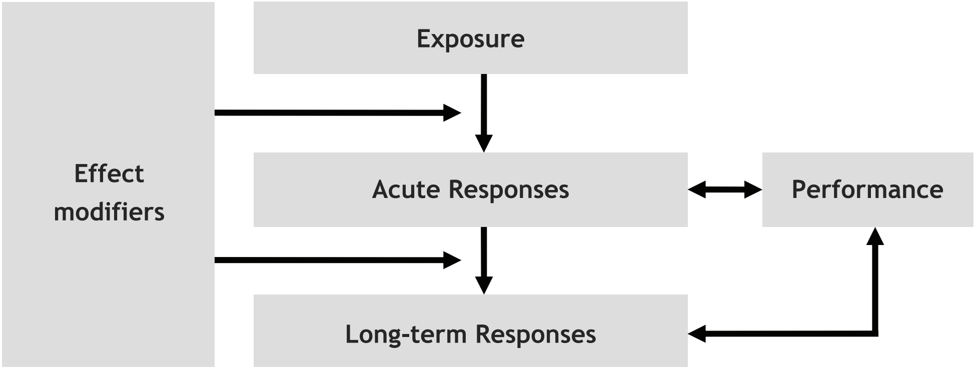


Figure 1-2. *Conceptual model describing the relations between exposure, acute responses, long-term responses, performance and effect modifiers (adapted from Winkel and Westgaard 1992, Winkel and Mathiassen 1994).*

Exposure

According to the literature the exposure depends on several work place factors, like work place design (e.g. working height), temporal aspects of work (e.g. rest breaks and duration), precision demands, speed of work, mental and visual demands (Sjøgaard and Jensen 2006) which in turn may lead to acute responses such as fatigue. For low-intensity work an effective strategy to reduce fatigue would be different from the traditional ergonomic work place adjustments or force-reducing measures. Here, modification of the temporal pattern of the load, e.g. by work duration modification, task variation or work pace optimization, might be more effective as compared to strategies reducing work intensity.

Acute responses: muscle fatigue

The main acute response which is addressed in this thesis is muscle fatigue. Muscle fatigue, or more specifically, localized muscle fatigue is an ongoing and continuous process (De Luca 1984) and is usually defined as an exercise-induced decline in the maximal force or power capacity of the muscle (Bigland-Ritchie and Woods 1984, Vøllestad and Sejersted 1988). It can also be defined as task failure or a decrease in capacity (Edwards 1983). However, during prolonged sustained low-force activities, muscles are able to maintain force levels and a reduction in force generating capacity does not necessarily occur, while physiological changes affecting the capacity of the muscle do (Moussavi et al. 1989, Sahlin and Ren 1989). Furthermore, recent studies on compensation or adaptation strategies suggest that people adapt their motor behavior to fatigue (e.g. Côté et al. 2005, Fuller et al. 2009) to unload fatigued body regions.

A wide range of methods has been used to detect manifestations of fatigue or physiological signs of fatigue during isometric contractions of short duration (e.g. electromyography, mechanomyography, micro-dialysis, near-infrared spectroscopy and rating scales of perceived fatigue or discomfort). Since the early studies of Piper (1912) and Cobbs and Forbes (1923), surface electromyography (EMG) has widely been used to study manifestations of muscle fatigue. EMG manifestations of fatigue are usually defined as a decrease in the frequency content accompanied by an increase in amplitude of the EMG signal (De Luca 1984, Basmajian and De Luca 1985). The increase in EMG amplitude is most likely attributed to additional motor unit (MU) recruitment (e.g. Moritani et al. 1986). Additional recruitment of larger MU's results in higher EMG amplitudes (e.g. Fallentin et al. 1993). The decline in frequency content, usually expressed as the mean or median power frequency, might be explained by a decrease in conduction velocity of the fiber membrane, changes in firing rates and synchronous MU discharge patterns (Hägg 1992).

Performance

Muscle fatigue has been associated with a decline of performance indicators. An impaired force steadiness as a consequence of fatigue has been reported (e.g. Seghers et al. 2003b). Furthermore, Björklund et al. (2000) showed diminished proprioceptive acuity following low-intensity work to fatigue and also impaired movement accuracy has been reported during fatigue (e.g. Jaric et al. 1999, Missenard et al. 2008). Even without the occurrence of disorders, fatigue might affect performance and can therefore be seen as an early form of presenteeism (i.e. productivity loss due to employees actually showing up for work while having disorders or experiencing discomfort). However, to the authors' knowledge there are no experimental studies showing the relation between muscle fatigue and performance during (simulated) occupational work tasks of low-intensity.

Long-term responses

Besides a factor affecting performance, muscle fatigue is often seen as an important initiating factor in the development of neck and shoulder muscle disorders (Valencia 1986, Rempel et al. 1992, Sejersted and Vøllestad 1993, Takala 2002). Even very low work loads in terms of a muscle's relative force (1-2%MVC) have been associated with elevated rates of occupational disorders (Veiersted et al. 1993, Aarås 1994, Westgaard et al. 2001). Muscle fatigue may be seen as a surrogate indicator of risk and as an exposure metric incorporating a range of underlying biomechanical and physiological influences (Nussbaum 2001). A relation between muscle tissue damage and increased fatigability during occupational work has been shown (Hägg 1991, Hägg 2000). Therefore, muscle fatigue when measured before, during and after work as a measure of physiological change of a muscle, may provide a biomarker for cumulative exposure to repetitive work.

Work-Related Upper Extremity Disorders (WRUED) which can originate from low-force activities, constitute one of the most serious work-related health complaints in Europe (Eurostat 2010). One fifth of the work-related health problems were associated with upper extremity problems. A review of the literature by Buckle and Devereux (2002) showed a 12-month prevalence among various EU countries ranging from 15 to 40%. In the Netherlands, the costs of WRUED were estimated at 2.1 billion Euros per year (Blatter et al. 2005). In Europe, almost two-thirds of the people with WRUED experienced some or considerable limitations in normal daily activities either at work or outside of work (Eurostat 2010). These limitations are an important concern not just for workers but also for employers. Presenteeism, productivity loss due to employees actually showing up for work while having disorders or experience discomfort, may have negative effects on a company's performance and can complementary to absenteeism lead to substantial costs. Although studies focusing on presenteeism and musculoskeletal problems are sparse, productivity losses as a consequence of working with WRUED were considered as a main cost driver and estimated at 808 million Euros per year in the Netherlands (Blatter et al. 2005).

Effect modifiers

Epidemiological reviews have shown strong and consistent associations between occupational exposures and neck and shoulder pain (e.g. Bongers et al. 2002, Punnet and Gold 2003). Beside the physical risk factors that have been identified in epidemiological reviews, like repetitive movements, prolonged static load and extreme working postures (Bernard 1997, National Research Council and Institute of Medicine 2001), several psychosocial risk factors have been reported in literature. An overview of longitudinal studies by Bongers and colleagues (2006) indicated that perceived stress and high demands in combination with low control at work are often related to neck and upper limb symptoms. Furthermore, several factors like individual characteristics (age, gender, etc.), motivation, work experience and skills may affect the relation between exposure, responses and disorders.

Specific relations to be addressed

The conceptual model in figure 1-3 illustrates the hypothesized relations between exposure to low-force work (work requirements), acute responses of the worker (muscle activity, manifestations of fatigue, perceived fatigue, kinematics) and performance which are specifically addressed in this thesis. Obviously, there are various responses to low-force activities like changes in intramuscular pressure, blood flow, metabolic changes, but in this thesis the focus is on manifestations of fatigue assessed by electromyography and rating scales only. The rationale for the selection of these methods can be found in their practical applicability and their proven added value as research instrument in occupational settings.

Although discomfort and fatigue may arise from different muscles, the upper trapezius muscle (m. trapezius pars decendens) is considered to be one of the most affected muscles in the shoulder region (Westgaard et al. 1996). The upper trapezius muscle is involved in stabilizing the shoulder girdle and participates as a primary mover in the elevation of the shoulder (Inman et al. 1944).

Furthermore, the trapezius muscle is easily accessible for non-invasive methods (like surface EMG) and is considered to be related to myalgic symptoms with a work related etiology (Westgaard et al. 1996).

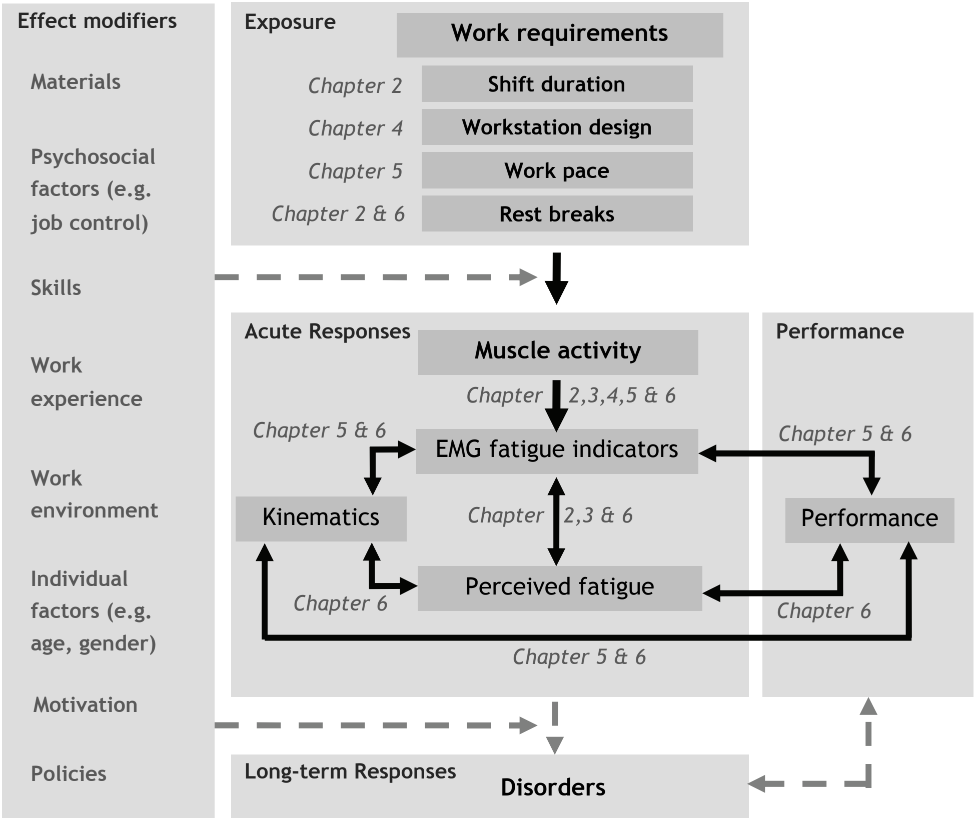


Figure 1-3. *Conceptual model describing the relations investigated in this thesis with the position of the individual chapters marked italic.*

Aims of the thesis

Assuming that muscle fatigue is a precursor of WRUED and may reduce performance of employees, it is important to get an improved insight in temporal patterns of loading during prolonged sustained low-force occupational work. The main objective of this thesis is therefore to assess:

"How EMG manifestations of muscle fatigue and perceived fatigue develop during low-intensity occupational work."

More specifically, I aimed to investigate the relations implied in the proposed conceptual model in figure 1-3 during prolonged low-force (occupational) work. The aims in this thesis were:

1. To assess whether EMG manifestations of muscle fatigue and perceived fatigue development can be detected during prolonged sustained low-intensity work.

2. To establish the effects of temporal aspects of the work (work duration, rest breaks and work pace) on the development of EMG manifestations of muscle fatigue and perceived fatigue.

3. To establish whether EMG indicators of muscle fatigue relate to feelings of local perceived discomfort and perceived fatigue.

4. To determine how EMG indicators of muscle fatigue relate to kinematics and performance in the task at hand.

Outline of the thesis

In **chapter 2**, a field study on manifestations of fatigue in catheter and shaver production is described. The relation between perceived fatigue and EMG manifestations of fatigue during real-life occupational work was investigated. Finally, the effect of shift duration in an occupational setting on muscle fatigue manifestations was studied. A review of studies investigating muscle fatigue in the neck and shoulder region during simulated or real-life occupational work is presented in **chapter 3**. The findings on the relation between EMG fatigue indicators and perceived fatigue are discussed as well as possible explanations for the absence of objective signs of fatigue development.

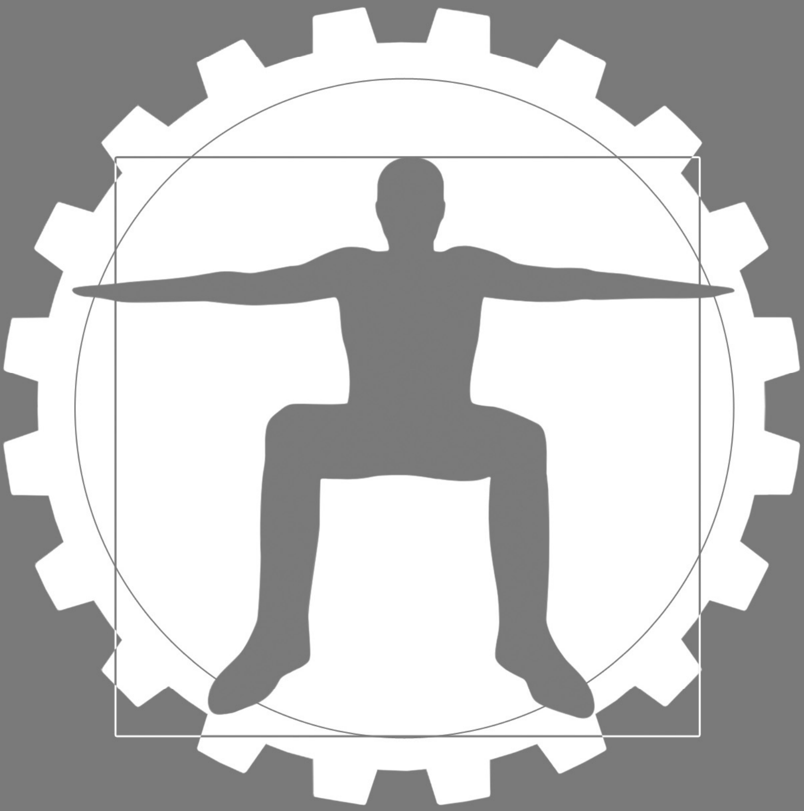
In **chapter 4** the development of fatigue manifestations during simulated assembly work was studied with isometric test contractions and continuous EMG measurements. A comparison was made between these two approaches and the effect of workstation design was evaluated. Different electrode positions on the upper trapezius muscle were studied to detect spatio-temporal changes in upper trapezius muscle activity.

In **chapter 5**, the effects of work pace on work load, work load variability and muscle fatigue in simulated repetitive assembly work were assessed. Muscle fatigue might be affected by changes in working posture or technique. Therefore changes in upper extremity kinematics were studied. Furthermore, work pace effects on performance, expressed as the number of errors, were investigated. In **chapter 6**, manifestations of fatigue development and their relation with changes in performance and timing strategy were investigated during more constrained short-cycle repetitive arm movements. The effect of short intermittent rest breaks on EMG fatigue indicators is discussed.

In **chapter 7** the findings of the studies in this thesis are summarized and discussed and recommendations for future research are presented. Finally, practical implications for low-intensity industrial work are presented in **chapter 8**.

Chapter 2

A field study on fatigue and discomfort during light manual work



"Development of fatigue and discomfort in the upper trapezius muscle during light manual work", Tim Bosch, Michiel de Looze & Jaap van Dieën, Ergonomics (2007), 50 (2), 161-177

Abstract

Optimization of the temporal aspects of task design requires a better understanding of the development of muscle fatigue in the neck and shoulder region over time. The objective of the study was to investigate this in two production companies and to determine the relation between electromyography (EMG) indicators of fatigue and feelings of perceived discomfort. EMG was recorded during standardized isometric test contractions. EMG amplitude increased during the day in both case studies while mean power frequency decreased only in one case. In both cases, a more detailed frequency analysis of the EMG signals showed an increase in lower frequency power accompanied by a decrease in higher frequency power. Local perceived discomfort in the neck and shoulder increased over the course of the day in both cases. However, no clear relation between perceived discomfort and objective indicators of fatigue was found.

Obtaining sufficient sensitivity to detect effects of temporal aspects of task design probably requires complementary or more refined methods (e.g. EMG arrays, mechanomyography).

Introduction

Work-related musculoskeletal disorders are common in industrial workplaces and contribute considerably to absenteeism (Sluiter et al. 2001, Buckle and Devereux 2002, Walker-Bone and Cooper 2005). A number of studies have identified occupational risk factors that are associated with musculoskeletal disorders. In particular, repetitive movements, high velocity and acceleration of movements, high external forces, prolonged static load on the muscles and extreme working postures are considered physical work-related risk factors (e.g. Kilbom 1994, Bernard 1997, Hägg 2000). It is, however, remarkable that work-related upper extremity disorders also occur in the absence of high force exertion and awkward body postures (National Research Council and Institute of Medicine 2001, Andersen et al. 2003). Even very low muscle strains in terms of the load intensity (1–2% maximal voluntary contraction (MVC)) are sometimes associated with elevated rates of occupational disorders (Aarås 1994).

Light-assembly work is a clear example of low-intensity work with elevated risks of neck and shoulder disorders (Aarås and Westgaard 1987, Hagberg and Wegman 1987, Mathiassen et al. 1993). In general, preventive measures concerning physical risk factors have been focused on reducing the intensity of musculoskeletal loads. Positive effects of load intensity-reducing measures, such as workstation redesign, have been described (McKenzie et al. 1985, Erisman and Wick 1992). Other studies, however, show that neck and shoulder disorders are rather impervious to work station improvements (Winkel and Oxenburgh 1990). If workstations are well designed and work intensity is low, strategies affecting the temporal pattern of the load might be more effective. These may concern the length of the working day, the work pace, the work – rest scheme or variations in tasks (Mathiassen and Winkel 1996). Questions about the optimal temporal pattern with regard to performance and health for low-intensity work situations are for the greater part unanswered. Several studies show that muscle fatigue is an important initiating factor in the development of neck and shoulder muscle disorders (Bjelle et al. 1981, Rempel et al. 1992, Sundelin and Hagberg 1992, Takala 2002). Therefore, muscle fatigue, when measured during work, may provide a relevant biomarker for cumulative exposure to repetitive work (Dennerlein et al. 2003).

In order to define the optimal time pattern of the work, a good understanding of the development of muscle fatigue over the course of a working day might be helpful.

The development of muscle fatigue at repetitive, low-intensity tasks has been studied on the basis of objective measurements (mainly electromyography (EMG)) and rating scales. In a laboratory study by Sundelin and Hagberg (1992), participants performed a pick and place task for 1 hour with their right arm. An increase in amplitude and a decrease in frequency content of the trapezius muscle EMG was found, while ratings of perceived fatigue in the shoulder muscle significantly increased.

Moreover, a significant relation between perceived fatigue and objective measurements of muscle fatigue was found. However, it remains unknown how muscle fatigue develops over longer working periods and whether the relation between objective indicators of muscle fatigue and perceived fatigue holds for longer periods interspersed with (short) rest breaks.

Suurküla and Hägg (1987) investigated the development of muscle fatigue in the trapezius and infraspinatus muscles after 2 hours working at the workplace. EMG variables showed a trend towards fatigue, but this was not statistically tested. Mathiassen and Winkel (1996) studied the assembly of starters of power saws. In a laboratory setting, they also found a trend towards increased muscle fatigue in the trapezius muscle over the course of a simulated 6-hours working day (with a 10% increase of amplitude and a 2.5% decrease in frequency content) but these changes were only partially significant. Perceived fatigue increased significantly during the working day but no clear statements were made about the relations between the objective and subjective measurements.

Bennie et al. (2002) and Dennerlein et al. (2003) investigated an isolated repetitive ulnar deviation task at a low-intensity level during a simulated 8-hours working day. Electrostimulation and EMG measurements of the extensor carpi ulnaris were used to detect muscle fatigue. A rating scale was used to investigate the development of local perceived discomfort. Both objective measurements showed an increase in muscle fatigue over the course of an 8-hours working day in the absence of perceived discomfort. In summary, the development of muscle fatigue in realistic working tasks has only received a little attention. Controversies remain on changes in objective and subjective fatigue indicators as well as on their relation.

In the present paper, two case studies are described that were performed at two different assembly companies. In the first case, participants worked for 4 weeks with normal 8-hours working days and 4 weeks with extended 9.5-hours working days. In the second case, employees worked 1 week with a 9-hours working day.

The general questions that both studies tried to answer were:

- How do objective estimates of muscle fatigue in the neck and shoulder region develop over a working day during repetitive low-intensity assembly work in a real-life occupational setting?
- How do objective estimates of fatigue relate to feelings of local perceived discomfort during low-intensity work?

In addition, two specific questions were investigated:

- How does muscle fatigue develop during an 8-hours working day compared to the fatigue development during a 9.5-hours working day (case study 1)?
- Is there a difference in the development of muscle fatigue on the first day of the week compared with the last day (case study 2)?

Methods

Case study 1

The first case study was carried out in a production unit of a Dutch manufacturer of medical instruments. Ten participants (four males and six females) participated in the study.

Table 2-1 shows the demographics of the sample. None of the participants reported any musculoskeletal disorders. All participants were experienced assemblers (5.7±1.0 years of experience). The participants gave their written informed consent prior to the start of the study. These participants assembled catheters by picking and placing small parts (Figure 2-1). They also performed the quality control for their own work by visual inspection. The work was monotonous, of low-intensity with static neck postures and repetitive arm lifting.

There was no regular task rotation. Workers were not paced by a driven production line, but worked at single or coupled workstations. The work pace was indirectly defined by a target (products per hour), but employees were free to take micro-breaks during the day. The intensity of the trapezius muscle load was not measured during the task but was estimated at 5% MVC.

***Table 2-1**. Demographics of the samples in the case study*

	Case study 1			**Case study 2**		
	Range	**Mean**	**SD**	**Range**	**Mean**	**SD**
Age (years)	25-52	38.5	8.0	37-46	42.1	2.6
Stature (cm)	160-190	161.8	10.7	160-172	166.3	4.4
Weight (kg)	58-98	69.3	12.5	62-100	74.5	13.0
BMI (kg/m2)	20-33	24.5	3.4	21-37	26.8	5.4

The participants first worked 8 hours per working day for a period of 4 weeks (normal days) followed by a 4-week period of working days of 9.5 hours (extended days). The day started at 07.00 hours and ended at 15.30 hours and 17.00 hours respectively in the two periods. Two coffee breaks of 15 min. were taken on normal days. On the extended working days, one 15-min. coffee break was taken in the morning and two 10 min. breaks were taken in the afternoon. There was a standard 30 min. lunch break. Measurements (described below) took place in the fourth week of the normal and the extended working day periods.

***Figure 2-1**. A double workstation for the assembly of catheters (left). A detailed view of the production of catheters in case study 1 (right).*

Case study 2

The second study took place at a Dutch manufacturer of shavers. A group of ten female participants participated in the study. None of the participants reported musculoskeletal disorders. All participants were experienced assemblers. The participants gave their written informed consent at the start of the study. Table 2-1 shows the demographics of the sample. The study took place on a driven production line where shavers were painted automatically. Production-line workers put on and removed small covers with a frequency of 18 movements/min (Figure 2-2). The work pace was determined by the speed of the sprayer. Natural micro-breaks were possible but people were not allowed to walk away. Workers rotated between workstations every hour, but the kind of activity did not change. A static neck posture and repetitive arm lifting were the most important characteristics of the workers' physical load. The work intensity on the trapezius muscle was not directly measured but was estimated to be similar to previous studies (e.g. Mathiassen and Winkel 1996) and was estimated at 15% MVC. The participants worked for one week with 9-hours working days. The day started at 14.00 hours and ended at 23.30 hours. Participants had a short 10 min. break every hour. There was a lunch break of 30 min. Measurements took place on Monday and Friday.

Figure 2-2*. Detailed view of the assembly task in case study 2. Picking the product (left), visual control (middle) and placing the product (right).*

Electromyography

A standard isometric test contraction with a duration of 30 s (Suurküla and Hägg 1987) was performed while the participants sat at their own work chairs and held their arms abducted at shoulder height at an angle of 90° (Figure 2-3). The position of the arms was controlled by horizontal flexible rods on stands.

Muscle activity was measured by means of surface EMG (porti 16/ASD system; TMS, Enschede, The Netherlands). Bipolar Ag/AgCl (Medicotest, Ambu A/S, Baltorpbakken 13, DK-2750 Ballerup) surface electrodes were placed with an interelectrode distance of 25 mm at the trapezius pars decendens muscles. The electrode positions were located according to Hermens et al. (2000). Electrode placement was controlled by an elastic cord. New electrodes were applied each working day. A reference electrode was placed on the C7 spinous process. Before the electrodes were applied, the skin was shaved, scrubbed and cleaned with alcohol. Skin resistance was not measured. EMG signals were amplified 20 times (Porti- 17TM, TMS, Enschede, The Netherlands, input impedance >1012 Ώ, CMRR >90 dB), band-pass filtered (10–400 Hz) and A–D converted (22-bits) at a sample rate of 1000 Hz. Mean amplitude was calculated by rectifying and low-pass filtering (2 Hz) the EMG signal. The amplitude values were normalized to the EMG values measured during the test contraction at the start of the working day. The mean power frequency (MPF) was analyzed using a fast Fourier transformation with a sliding window of 1000 samples with a 500 sample overlap between consecutive windows. The MPF values were normalized to the measurement at the beginning of the working day. Using the power spectra, six frequency bands of 50 Hz were used to analyze the frequency content in more detail (Dolan et al. 1995). The first band was 10-50 Hz, the next 50-100 Hz and so on, up to 300 Hz. The mean power of each band was calculated. The relative power of each band in relation to the total power was determined by dividing the mean power of each band by the total power.

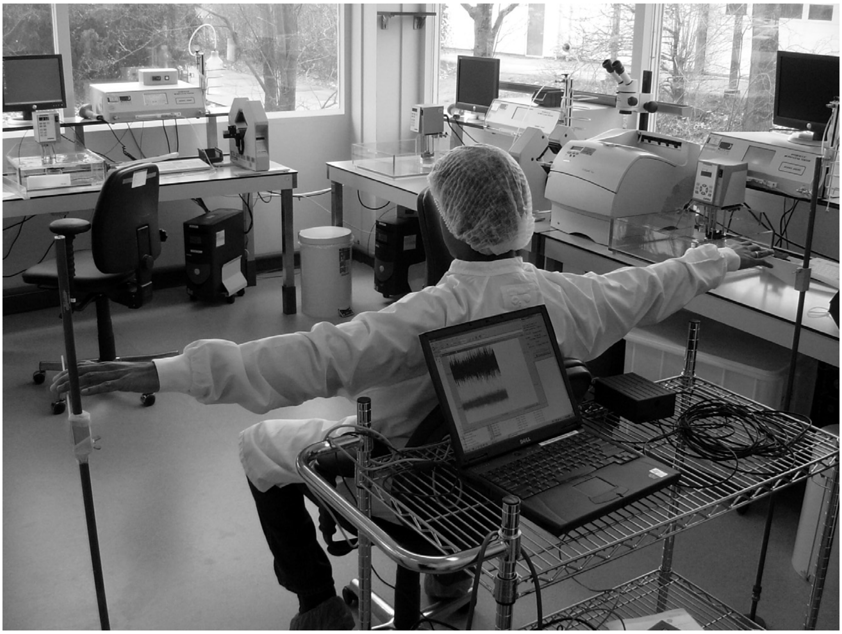


Figure 2-3. *The electromyography isometric test contraction.*

Discomfort

Discomfort was measured using the local perceived discomfort method (van der Grinten 1991). A body map consisting of four regions in the neck and shoulder was presented to the participants. Participants were asked to rate discomfort in the regions identified on a 10 point-scale (ranging from 0= no discomfort to 10= extreme discomfort, almost maximum). The highest discomfort score in the four regions was defined as the score for discomfort.

In the first case study, EMG and discomfort measurements were performed four times on both days (before starting, before and after the lunch break and at the end of the day). On the extended day an extra measurement was made at the end of the eighth hour. The schedule of discomfort measurements is shown in figure 2-4a and b.

In the second case study, measurements were obtained before the beginning of the day’s work, before and after the lunch break and at the end of the working day (as shown in Figure 2-4c).

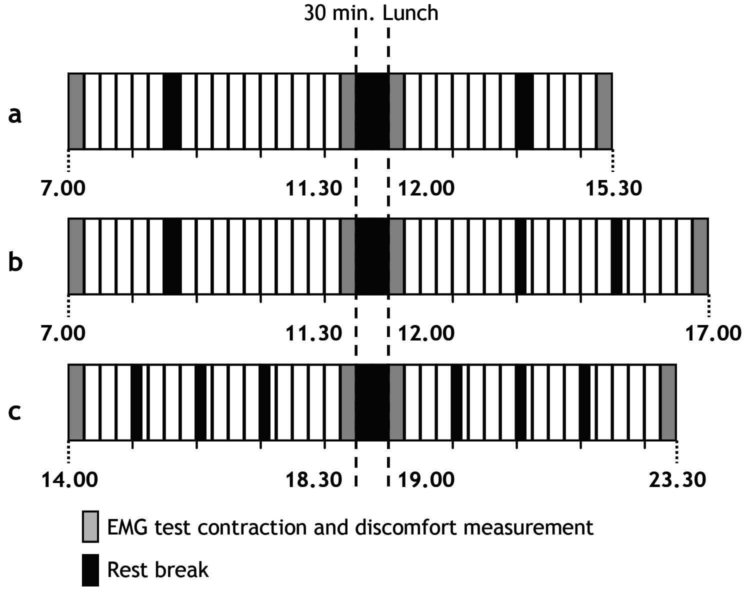


Figure 2-4. a*. The normal working days in case study 1;* ***b****. The extended working days in case study 1;* ***c****. The working days in case study 2.*

Statistical analysis

Data were analyzed with a repeated measure ANOVA to compare the independent variables (days (2) and time moments (4)) for all dependent variables (EMG amplitude, MPF, relative power in each frequency band and local perceived discomfort). Two additional ANOVA's were used to evaluate the effects on the relative power in each frequency band for the separate daily periods (before lunch and after lunch). p-Values were based on degrees of freedom corrected with Greenhouse-Geisser's epsilon to compensate for the effects of violations of the sphericity assumption. A Student's t-test was used as the follow-up test for comparisons of means. On the normal working day of the first case study, two EMG measurements were missing (for two different participants).

Missing values were replaced by using the mean relative change of the whole group. Pearson's product moment correlation was calculated to determine the relations between objective EMG variables and discomfort. Significance was accepted at $p<0.05$.

Results

Mean power frequency and amplitude of the EMG: case study 1

In case study 1, no significant temporal changes in the MPF were found (Figure 2-5a). Furthermore, there were no significant differences in the relative changes of the MPF between the normal and the extended working days (p=0.211). For the amplitude of the EMG signal, a main effect of time was found (p=0.007). A post-hoc test revealed a significant increase in the first period of the day (p=0.005). The amplitude did not change over lunch or the second period of the day. There were no significant differences in the relative changes in amplitude (p=0.203) found between the normal and the extended working days (Figure 2-5b).

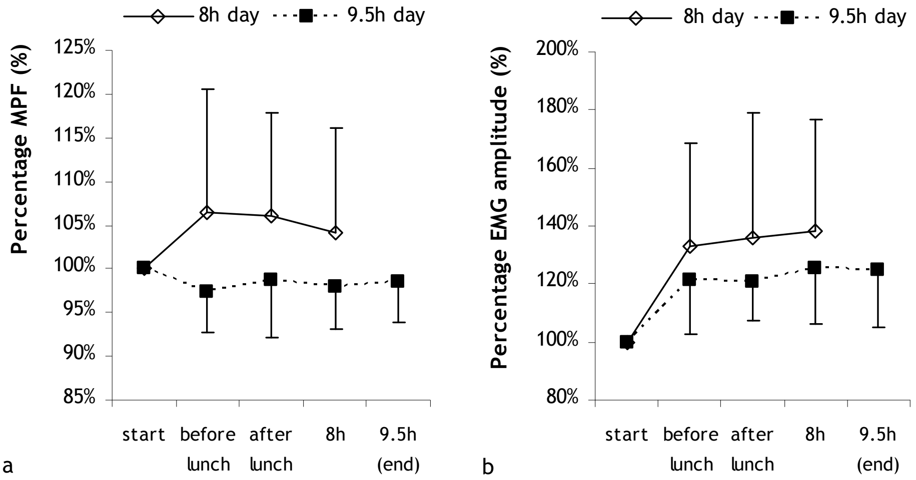


***Figure 2-5**. **a**. The relative changes in the mean power frequency (MPF) in case study 1 for the extended and normal working days; **b**. the relative changes in EMG amplitude during the extended and normal working days in case study 1. Error bars represent standard deviation (SD) between participants.*

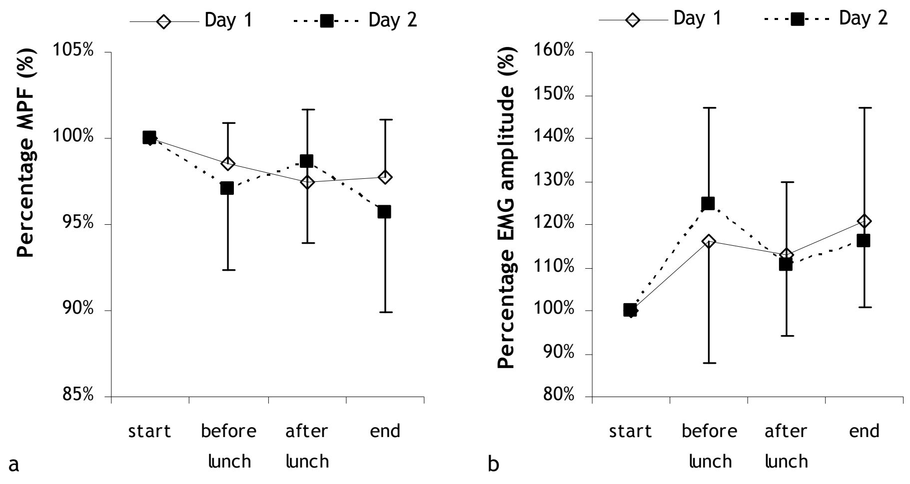


***Figure 2-6**. **a**. The relative changes in the mean power frequency (MPF) in case study 2 for the first and last days of the week; **b**. the relative changes in EMG amplitude during the working days in case study 2. Error bars represent SD between participants.*

Mean power frequency and amplitude of the EMG: case study 2

In case study 2, a significant temporal change in the MPF was found (p=0.021). A post-hoc test showed that the MPF decreased in the period before lunch (p=0.021). The increase of the MPF during the lunch period, which may have indicated muscle recovery, was not significant (Figure 2-6a). A main effect of time was also found for the amplitude of the EMG (p=0.014). A post-hoc test revealed a significant increase in the first period (p= 0.011). Other temporal changes during the working day were not significant (Figure 2-6b).

With regard to the development of fatigue over the working week, the relative decreases of the MPF and the relative increases in amplitude on both working days did not differ significantly.

Frequency Banding

If muscle fatigue is present, an increase in lower frequency bands and a decrease in higher frequency bands over the course of a working day are expected. However, an ANOVA with measurement time and frequency band did not show a significant interaction between the relative power in frequency bands and time for either day in case study 1. An additional ANOVA was used to investigate the change over time separately for the periods before and after lunch. On the extended working days, the relative power of the lower frequencies increased significantly (p=0.033) accompanied by a significant reduction of higher frequencies (p=0.008). No other significant temporal changes were found (Figure 2-7).

In case study 2 (Figure 2-8), a significant interaction between frequency band and time was found on the second working day (p=0.023). A post-hoc test showed an increase in relative power (p=0.05) in lower frequency band (10-50 Hz) in the period after lunch accompanied by a significant reduction (p=0.001) of relative power of the higher frequencies (100-150 Hz). In the first period of the second working day, the increase in power of the lower frequencies (10-50 Hz) was not significant but a trend to an increase in power existed (p=0.08). The decrease of the higher frequencies was, on the other hand, significant (p=0.018). There were no significant interactions found on the first day of the week.

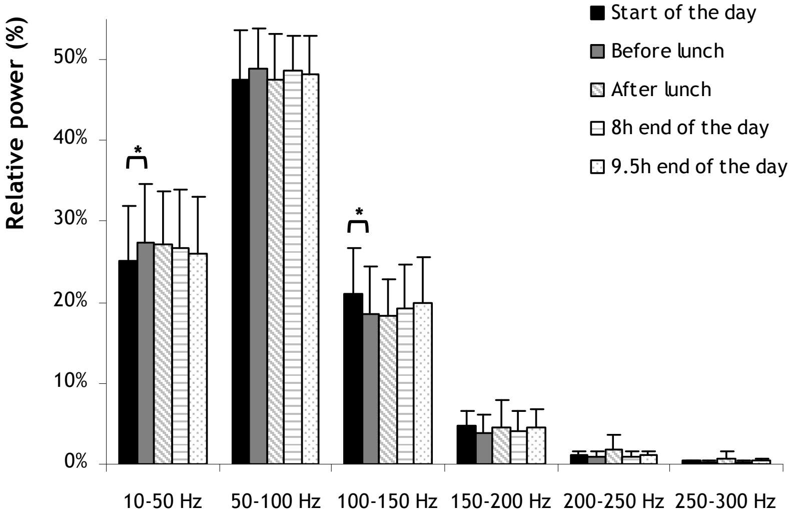


Figure 2-7*. Relative power of each frequency band in relation to the total power on the extended working day of the first case study. The low frequency band (10-50 Hz) significantly increased before the lunch, which was accompanied by a significant decrease in higher frequencies (150-200 Hz), indicated by *. Error bars represent SD.*

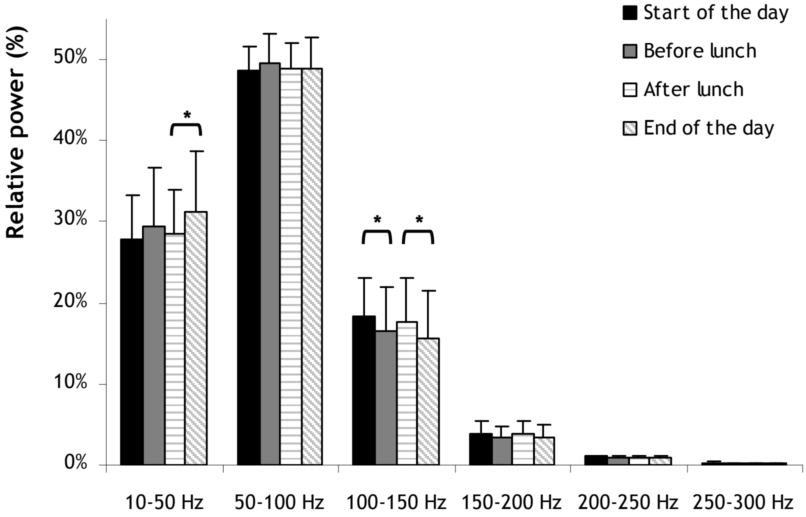


***Figure 2-8**. Relative power of each frequency band in relation to the total power on the second day of case study 2. The low frequency band (10-50 Hz) significantly increased after the lunch accompanied by a significant decrease in higher frequencies (150-200 Hz), indicated by *. Error bars represent SD.*

Discomfort

Figure 2-9 shows the development of discomfort in the neck and shoulder region for both case studies. The variation in neck and shoulder discomfort across participants was large.

In case study 1, a main effect of time on discomfort in the neck and shoulder region was found (p=0.007). Post-hoc tests revealed significant increases during the first (p=0.016) and second (p=0.05) period of the day. The decrease of discomfort during the lunch period, which may have indicated recovery, was not significant (p=0.153). Discomfort was significantly higher on a 9.5-hours working day in comparison to an 8-hours working day (p= 0.019). However, no significant increase in discomfort was found in the extended work period (the final 1.5 hours).

In case study 2, a significant temporal change of discomfort in the neck and shoulder region was found (p=0.017). Post-hoc tests showed significant increases during the first (p=0.023) and second (p=0.012) periods of the day. Discomfort did not decrease during the 30 min. lunch break (p=1.0). Discomfort on the first and last working days of the week did not differ significantly.

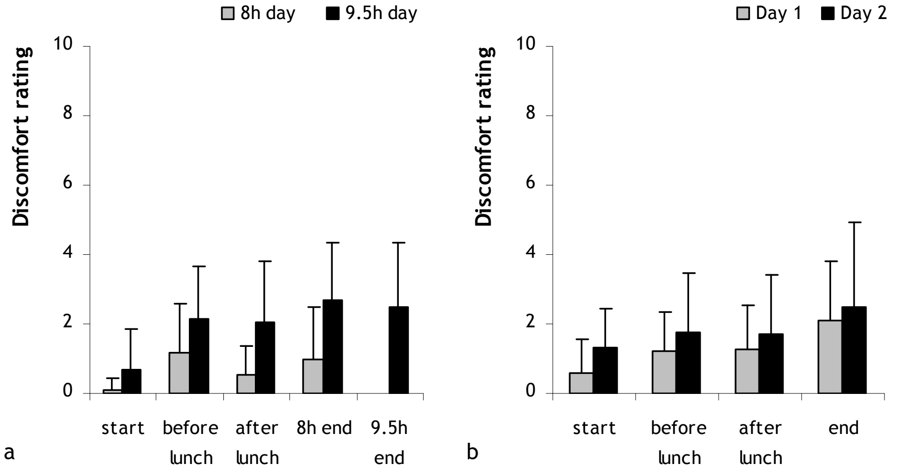


***Figure 2-9*. *a*. Case study 1: discomfort in the neck and shoulder region for the extended and normal working days; *b*. Case study 2: discomfort in the neck and shoulder region for the first and last days of the week. The discomfort rating scale ranged from 0 to 10 (almost maximum). Error bars represent SD.**

Correlation between variables

Pearson's correlation coefficients were determined for the difference between the start and the end of the day (Table 2-2) and the differences between the start and end of the working periods before and after lunch for EMG amplitude, MPF and discomfort ratings (Table 2-3). No relation was found between EMG manifestations of muscle fatigue and perceived discomfort. Correlation coefficients were low and not significant.

Table 2-2*. *Pearson correlation coefficients (r) and p-values for associations between, on the one hand, EMG indicators of fatigue development and on the other feelings of perceived discomfort.

	Case study 1	**Case study 2**
	r (p-value)	r (p-value)
EMG Amplitude – discomfort rating	0.13 (0.176)	- 0.01 (0.975)
EMG MPF – discomfort rating	- 0.59 (0.074)	- 0.45 (0.192)

***Table 2-3**. Pearson correlation coefficients (r) and p-values for associations between, on the one hand, EMG indicators of fatigue development and on the other feelings of perceived discomfort during different work periods.*

	Case study 1		**Case study 2**	
	Before lunch	After lunch	Before lunch	After lunch
	r (p-value)	r (p-value)	r (p-value)	r (p-value)
EMG Amplitude - discomfort rating	0.17 (0.963)	-0.51 (0.137)	-0.38 (0.282)	0.07 (0.843)
EMG MPF - discomfort rating	-0.39 (0.264)	0.38 (0.279)	0.38 (0.274)	-0.63 (0.051)

Discussion

In the current study, the development of muscle fatigue over the course of a working day was investigated in two production companies together with the relation between subjective and objective estimates of fatigue. This type of field research has some limitations in comparison with controlled laboratory experiments. The time period as well as the number of participants is often restricted. In addition, there are many confounding factors related to production planning, capacity utilization, variation in products, (technical) disturbances and absence of participants. These confounders are hard to control and have large effects. Conversely, field research has the obvious advantage that it requires no extrapolation of results to practice.

The EMG signals obtained in this field study showed indications of the development of muscle fatigue over the course of a working day. Indications of muscle fatigue include an increase of the EMG amplitude and a decrease of the MPF (Basmajian and De Luca 1985). In case study 1, EMG amplitude increased during the first part of the day while the MPF did not change significantly over time. In case study 2, an increase in amplitude of the EMG signal was accompanied by a decrease of the MPF during the first part of the day. A more detailed analysis of the frequency content (Dolan et al. 1995) showed an increase of the lower frequency band (10-50 Hz) accompanied by a decrease of the 100-150 Hz band in the first period of the second working day. As stated before, muscle fatigue might be an initiating factor of muscle disorders but the relation between muscle fatigue and disorders was not investigated in this study.

Case study 2 demonstrated stronger indications of the development of muscle fatigue than case study 1. This may have been due to a higher work intensity in case study 2. The participants' work pace in case study 1 was not driven by a production line. Participants were free to move and had more opportunities to take short breaks, in contrast to the participants in the second case study, who had a strictly determined work pace. In addition to the higher work pace, participants in the second case study had to lift their arms higher and with a higher frequency. Furthermore, the participant groups clearly differed between the two case studies. In the first case study, a mixed gender population was involved (six females and four males), while in the second case study only females were involved. Gender might be a bias and therefore no systematic comparison was made between the two cases.

No differences were found between the different working days. The extended working days did not show more signs of fatigue than the normal (8-hours) working days (case study 1) and the last day of the week did not differ from the first day (case study 2). Only relative changes in EMG variables during the day were compared. Absolute MPF and amplitude values could be higher on the second day, but it was not possible to compare absolute differences as the electrodes were replaced in between days. Electrode location was visually controlled carefully, but small changes in electrode position may have occurred and skin resistance was not controlled.

The EMG signals in this study were obtained during test contractions. Under dynamic conditions, factors that hardly can be controlled (such as muscle length, muscle-electrode distance and movement velocity) may lead to erroneous interpretation of the EMG signals (Madeleine et al. 2001). Previous studies obtained positive results (Suurküla and Hägg 1987, Mathiassen and Winkel 1996) with a test contraction method. The test contraction used allows the recording of stationary signals that are likely to be produced by the same pool of motor units in every measurement. On the other hand, it is not known whether a contraction is representative of the workload and thus of the motor unit recruitment during the real task (Søgaard et al. 2003, Blangsted et al. 2005). An additional disadvantage is the disruption of the work process.

In addition to the indications of the development of objective muscle fatigue, local perceived discomfort in the neck and shoulder region was also found to increase in both case studies. Remarkably, there was no clear relation between subjective indicators (perceived discomfort in the neck and shoulder region) and the objective indicators (MPF and amplitude of the EMG signal) of muscle fatigue. Sundelin and Hagberg (1992) were able to find a significant relation between subjective (discomfort) and objective indicators (MPF and amplitude of the EMG of the trapezius muscle). However, that study used a 1-hour strictly controlled laboratory task with a relative high intensity and measurement frequency (12 times/hour). No such relation has been established so far, to the present authors' knowledge, in field research over the course of a working day. The absence of a relation might be explained by several factors. First, the ratings of local perceived discomfort obtained in occupational settings might be the result of other issues rather than discomfort. For instance, the subjective interpretation of an intervention (e.g. longer working hours) might influence the participants' feelings of discomfort. Moreover, discomfort also encompasses sensations of other sensory experiences such as pain and pressure as well as discomfort in tissues other than the muscles. Conversely, EMG measurements reflect only a small part of the physiological state of the muscle.

Changes in the MPF and amplitude of the EMG signal are less consistent during prolonged low-level dynamic contractions than during high-force contractions (Nussbaum 2001, Søgaard et al. 2003). Physiological processes not reflected in the EMG signal (e.g. local blood flow, local metabolic changes, changes in the mechanical properties of the excitation contraction coupling) may play an important role in the development of fatigue during low-intensity work. This study showed signs of fatigue but differences between conditions (normal vs. extended days, first vs. last day of the week) were not found. To be able to detect such differences, complementary objective methods may be needed. Possibly the use of multiple surface electrode pairs on the muscle will increase sensitivity of EMG bases (Staudenmann et al. 2005). Activity of the trapezius muscle in this study was measured using one bipolar surface electrode pair. This is adequate if the muscle is homogeneously activated. However, this may not be the case during assembly work. Different muscle compartments may be activated independently during the performance of different elements of the tasks (Jensen and Westgaard 1995, Jensen and Westgaard 1997, Kleine et al. 1999). Therefore, the sensitivity of the estimations of upper trapezius muscle fatigue could be increased by using multi-electrodes. Blangsted et al. (2005) used mechanomyography (MMG) to detect fatigue during short, low-intensity static contractions. Physiological features such as motor unit recruitment and synchronization of motor units are thought to be reflected by MMG measurements (Orizio et al. 2003) and could provide additional information on fatigue processes. Rosendal et al. (2004b) used microdialysis to investigate intramuscular metabolism of the trapezius muscle during a 20-min. repetitive low-force contraction exercise.

An increase in pain was accompanied by a rise in local anaerobic metabolism. However, the use of this method in field studies is likely to be limited.
An increase in discriminatory power may be required here and these methods could help to achieve just that. This might further help in the definition and justification of temporal interventions such as changing the length of the working day, introducing extra pauses or task variation across time.

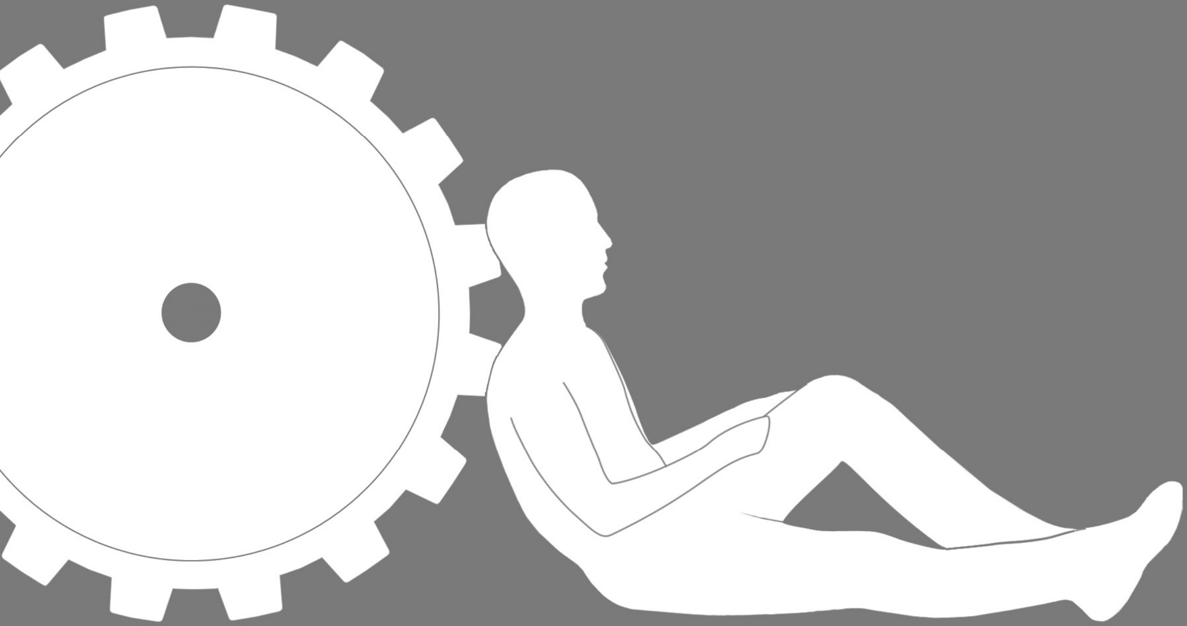
In conclusion, the development of muscle fatigue was indicated by both objective and subjective measurements. However, no clear relation between the subjective and objective indicators of muscle fatigue was found.

Acknowledgements

The authors acknowledge Philips DAP and Cordis Europe for their support.

Chapter 3

Fatigue in prolonged activities involving low-force contractions: a review



"Manifestations of shoulder fatigue in prolonged activities involving low-force contractions", Michiel de Looze, Tim Bosch & Jaap van Dieën
Ergonomics (2009), 52 (4), 428-437

Abstract

Shoulder fatigue has been suggested to be a useful risk indicator for shoulder disorders in repetitive, low-force work tasks. In contrast to high-force or purely isometric tasks, it is unclear whether measurable fatigue develops in realistic low-force work. The question addressed in this review was: 'Is there evidence of objective signs of fatigue in the shoulder region in realistic, low-force work tasks?' Studies on objective measures of fatigue applied in realistic low-force work tasks were systematically reviewed, using a task duration of more than 1 hour and an intensity level of less than 20% maximum voluntary contraction (MVC) for the mean or median trapezius activation level as inclusion criteria. Thirteen studies were found to fulfill the criteria. All these studies addressed fatigue-related changes in the electromyographic signal in the descending part of the trapezius muscle. Seven did find a combination of frequency decrease and amplitude increase over time, which is generally considered as an objective manifestation of fatigue. Thus, there is evidence of objective signs of fatigue in some of the realistic, low-force tasks. The intensity level appeared to be a main determinant here. In the studies demonstrating signs of fatigue an intensity level of 15% MVC or more was used, while the intensity level in the studies with a negative result was generally lower.

Introduction

Monotonous activities involving repetitive hand and finger movements at low force levels are increasingly common in daily life, both in terms of numbers of people exposed to these activities and in terms of individual exposure times. This shift is mainly due to the widespread automation of work processes promoting activities such as computer work in offices and other settings, joystick steering and control in construction, distribution, transport, refuse collecting and light pick-and-place tasks in manufacturing. The frequent use of computers at home, when surfing on the Internet,
e-mailing, chatting, and gaming, further contributes to this phenomenon.
Despite the low force levels involved, these types of activity are not without musculoskeletal health risks, particularly in relation to the shoulder girdle region. For many years it has been assumed that muscular contraction levels at 15% maximum voluntary contraction (MVC) are acceptable in the workplace (Rohmert 1973), but this assumption has changed over the years. It has been shown that musculoskeletal disorders in the shoulder region are frequent even in jobs with force levels of 2-5%MVC (Jonsson 1988). Others reported that shoulder problems may relate to muscle loads as low as 0.5 to 1% (Veiersted et al. 1990, Jensen et al. 1993a). Most recently, statements have been brought forward that muscle loads are not acceptable at all if sustained over longer periods of time (Sjøgaard and Jensen 2006). Shoulder disorders that are related to low-level activities are generally assumed to be muscular in nature. They result from several underlying mechanisms such as blood flow impairment, accumulation of Ca^{2+}, muscle damage due to internal shear forces and selective motor unit recruitment (Visser and van Dieën 2006). The exact nature of these mechanisms, the plausible interactions and any dose relationships are as yet not clear.

Many hypothesize that shoulder muscle fatigue is a precursor of shoulder complaints (e.g. Herberts and Kadefors 1976, Rempel et al. 1992, Takala 2002). If so, muscle fatigue when measured during work would be a relevant biomarker for cumulative exposure to repetitive work and a surrogate indicator of risk, and as such may help to prevent health problems (Nussbaum 2001, Dennerlein et al. 2003). This suggestion presumes that in low-force activities not only muscle fatigue develops, but also that this fatigue development can be measured. Compared to activities at high-level forces, the occurrence of fatigue due to low-force activity is poorly understood. In high-level activity, major intramuscular changes related to blood flow, water fluxes, temperature and metabolite concentrations occur, which result in the development of fatigue, directly demonstrated by a decrease in the maximal muscle strength (e.g. Asmussen 1993). Moreover, manifestations of muscle fatigue can be observed in the electromyographic (EMG) signals in the fatigued muscles. Extensive evidence specifically shows that the EMG signal amplitude increases while the frequency spectrum shifts towards lower frequencies (Basmajian and De Luca 1985). In low-level activity, however, only subtle intramuscular changes occur and the maximal muscle strength or other measures of performance may not detectably decrease. Using a strict definition of fatigue as a demonstrable loss in performance (e.g. Bigland-Ritchie and Woods 1984), one might state that fatigue in low-level activity does not even occur. However, fatigue is not only defined in terms of performance changes but also in the perceptual and physiological domain (Åhsberg 1998). In this respect, it is interesting to note that various authors reported increases in perceived fatigue or discomfort due to low-level activities (Sjøgaard et al. 1986, Byström and Kilbom 1990). But are these findings of perceived fatigue supported by any measurable physiological changes? It might well be that in stages where performance is not (yet) affected, the contractile capabilities of muscles are hampered and homeostatic disturbances may occur that in the long run may induce chronic morphological changes (e.g. Blangsted et al. 2005).

In the present report, studies on objectively measurable fatigue-related changes in time in low-level force activities were reviewed. The review was limited to the repetitive low-level force activities that are typical for the type of occupational tasks that were mentioned before. Inclusion was limited to studies on the shoulder region; only studies investigating shoulder fatigue were included.
The research question was: Is there evidence of objective signs of fatigue in the shoulder region during realistic low-force work tasks?

Methods

This review was based on an electronic literature search in Medline (1950–August 2007) and NIOSHTIC2, CISDOC, HSELINE, MHIDAS and OSHLINE (1985–August 2007). The keywords used were: muscle fatigue; low frequency fatigue; discomfort; low intensity; light manual work; office; computer work; assembly work; static; dynamic; Visual Display Unit or VDU; electromyography; blood flow; mechanomyography; Near Infrared Spectroscopy or NIRS; position sense. The references retrieved by this search were first screened on the basis of their abstracts. In cases where the abstracts did not provide sufficient information, the full paper text was screened. The papers apparently fulfilling the inclusion criteria (see below) were selected for further study. The literature retrieved in this way was supplemented with studies cited in the retrieved papers. Finally, personal databases of the authors were searched for relevant papers.

To be included, studies had to be published in peer-reviewed journals in the English language and should consider the development of fatigue in the shoulder region. The other inclusion criteria were related to the type, duration and intensity of the task under investigation and the method to obtain objective information about fatigue.

As the researchers were interested in the typical repetitive, long-lasting and low-force occupational activities that are common in daily occupational life, studies on fatigue due to purely isometric muscle contractions were not considered in this review. This review did include studies on occupational tasks simulated in the laboratory as well as studies on occupational tasks performed in real life. Next, studies on activities at high-force levels were excluded from this review. In studies where the intensity of the workload was expressed as a percentage of the maximal EMG activity of the trapezius muscle (pars descendens), a percentage of 20% was used as a cut-off point. Additionally, studies on computer work, light manual work and assembly work were included, as for these type of activities the intensity levels in terms of median EMG amplitudes reported in the literature are generally below 20% MVC (Westgaard et al. 1996, Thorn et al. 2007). Another inclusion criterion related to the task was a total duration of the task of 1 hour or more. Both studies on continuous tasks and studies on tasks that were interrupted by rest breaks were included. Finally, all studies had to apply an objective measuring method to assess the development of fatigue over time. Among the potential measuring methodologies and parameters were electromyography (EMG), mechanomyography (MMG), blood oxygen saturation and position sense. With regard to the EMG and MMG studies, only studies that considered both the power spectrum and the signal amplitude were included, as it is typically the combination of a power frequency decrease and amplitude increase that indicates the development of fatigue (Basmajian and De Luca 1985).

Results

The search strategy resulted in 137 hits. The first screening of the abstracts resulted in the exclusion of 41 papers for various reasons (e.g. no realistic task, not a task involving the shoulder muscles, no study of fatigue development over time). After application of the selection criteria while considering the full text, another 83 papers were excluded, mainly because of another body region of interest than the shoulder (30 studies), a too short task duration (25 studies), the study of purely isometric muscle contractions (11 studies) and a level of intensity too high (6 studies). In a few papers, the issue of fatigue was addressed, but not its temporal development. Four EMG studies fulfilling all other selection criteria either considered the power spectrum or the signal amplitude, but not the combination of the two.

The remaining 13 papers are presented in table 3-1. Out of these 13, there were eight studies on tasks performed in the laboratory and five studies on occupational tasks performed in real life. The tasks concerned computer work in two studies, assembly work or simulated assembly work in five studies and other tasks such as driving, sewing, drilling and dentistry. There appeared to be a large variation in task duration across the various studies, ranging from 1.0 to 9.5 hours. It is noticeable that the size of the samples in some of the studies is fairly small. The level of intensity if expressed as a percentage of the EMG amplitude in a MVC (in five studies) ranged from 3-6 up to 16%. Other studies, which did not specify the load intensity, were included because the intensity levels were assumed to remain below the 20% cut-off point. However, one might question here the inclusion of several papers. The study of Sundelin (1993) was included on the basis of the median amplitude of the peak load of 31%. The studies of Hostens and Ramon (2005) and Kimura et al. (2007) were also given the benefit of doubt, not knowing the load intensity of car driving and keyboard typing with the wrists loaded by 1 kg, respectively. Surprisingly, none of the included studies applied a measuring method other than electromyography. In all these EMG studies, the activation of the descending part of the trapezius was analyzed. In some, the activation of the infra spinatus or deltoid muscles was additionally studied, but fatigue manifestations were always more prominent in the trapezius and, thus, these are reported table 3-1.

Considering these results, six studies found objective evidence for manifestations of muscle fatigue within the muscle, as deduced from a combination of a frequency decrease and an amplitude increase. In two studies, however, no such changes in power frequency and amplitude were observed. In the remaining five studies, only one of these changes occurred, either an increase in amplitude (in four studies) or a decrease in the frequency content (in one study).

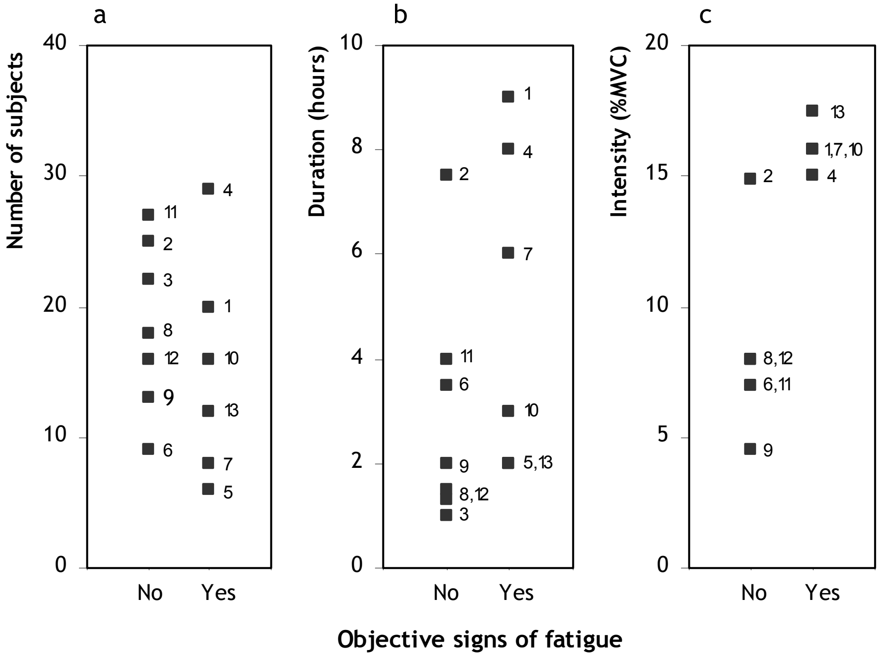


***Figure 3-1**. **a**. Number of subjects; **b**. Task duration **c**. Intensity level in the studies included in this review. MVC = maximum voluntary contraction. Studies showing objective signs of fatigue are separated from the other ones.*

Table 3-1*. Overview of the results. Only results significant at $p < 0.05$ are presented (in 7th and 8th column). In the final column, '+' means that an EMG amplitude increase and frequency decrease was found, '-' means that none of these changes were observed, and 'o' refers to the situation where only one of these changes was found.*

Study	Nr. subjects	Task	Duration	Intensity	Measurements	Perceived fatigue development	Objective manifestations of fatigue development	Objective evidence for fatigue
1. Bosch et al. 2007	16F 4M	assembly of catheters (A) and picking and placing of covers of shavers (B)	8.5-10 h (A) 9.5 h (B) including pauses	not specified	EMG-test LPD (10)	shoulder discomfort increase from 0.5 to 2	ARV increase by 27% (A) and 19% (B) Decrease in higher frequency bands by 4% (A) and 11% (B) and MPF decrease by 3% (in B only)	+
2.Christensen 1986	16F 9M	picking and assembling printed circuits (F); soldering and assembling chasses (M)	7 h 30 min. including pauses	14.9%	EMG-task & test HR RPE (9)	RPE increase from 1 to 3-4 (F); from 2 to 3 (M)	RMS (task): no change MPF(test): no change	-
3. Hostens & Ramon 2005	22M	driving on a private asphalt road	1 h	not specified	EMG-task		RMS decrease Instantaneous MPF decreases in active muscle parts	o

Table 3-1. *Continued.*

Study	Nr. subjects	Task	Duration	Intensity	Measurements	Perceived fatigue development	Objective manifestations of fatigue development	Objective evidence for fatigue
4. Jensen et al. 1993a	29F	sewing machine operation	8 h including pauses	15%	EMG-test Muscle strength RPE (10)	RPE increase from 1-3	RMS increase by 3% MPF decrease by 4% Maximal muscle strength: no change	+
5. Kimura et al. 2007	6M	computer work: writing by keyboard +1kg load on wrists	1 h 55 min. including three pauses (5 min)	not specified	EMG-test RPE (4)	RPE increase from 0 to 1-3	RMS increase by 14.8% MPF decrease by 10.6% CV decrease by 13.6%	+
6. Kleine et al. 1999	9F	computer work: writing by keyboard	3 h 30 min. including two 15 min. pauses	not specified	EMG-task		RMS increase by 17, 18, 22% (in 1st, 2nd and 3rd hour); MPF no changes	o
7. Mathiassen & Winkel 1996	8F	laboratory simulation of assembly of starters for power saws	6 h including pauses	not specified (30% MVC was exceeded during 5% of working time)	EMG-test RPE (10) PPT (10)	fatigue from 1 to 5 PPT decrease by 10-15% in initial hours	RMS increase by 11%, zero- crossing rate decrease by about 2.5%	+

Table 3-1. *Continued.*

Study	Nr. subjects	Task	Duration	Intensity	Measurements	Perceived fatigue development	Objective manifestations of fatigue development	Objective evidence for fatigue
8. McLean et al. 2000	15F 3M	computer terminal work	1 h and 20 min. with and without micro breaks	not specified	EMG-task		RMS: no change MPF: no change	-
9. Nakata et al. 1992	13F	laboratory simulation of assembly work: picking nails and screws and inserting them into holes in boards	2 h	3-6%	EMG-test LPD (10)	LPD increase from 0.5 to 2.2 in right shoulder	RMS increase by 27% in ‘high discomfort subgroup’ only MPF: no significant decrease	o
10. Nussbaum 2001	8F 8M	laboratory simulation of overhead assembly: tapping motions between two targets above shoulder	3 h or until exhaustion	16%	EMG-task & test		RMS decrease by 9.2% (test) and 12.9% (task) per hour; 57% of participants show amplitude increase (task) MPF decrease by 0.9 (test) and 1.3% (task) per hour 55% show MPF decrease (in task)	+

***Table 3-1**. Continued.*

Study	Nr. subjects	Task	Duration	Intensity	Measurements	Perceived fatigue development	Objective manifestations of fatigue development	Objective evidence for fatigue
11. Rolander et al. 2005	17F 10M	dentist work	about 4 h including pauses	5-9%	EMG-task		ARV increase by 14%; MPF: no change	o
12. Seghers et al. 2003a	8F 8M	computer work: keyboard and mouse	1 h and 29 min.	not specified	EMG-task local dis-comfort (10)	no statistical results provided	ARV increase by 5% MPF: no change	o
13. Sundelin 1993	12F	repetitive grasping a small cylinder and releasing it through a hole	2 h, one hour without pauses and one hour with pauses	not specified (median value of peak load: 31% median value of static load: 4.4%)	EMG-task RPE(20)	RPE from 0 to 12-14	In eight participants a combination of RMS increase 18-40% per hour MPF decrease 2-15% per hour	+

Explanation of used terms and abbreviations: M and F indicate the male and female gender, respectively;
Intensity is expressed by the mean or median initial trapezius activation in %MVC;
EMG-task and EMG-test refer to the cases where EMG is obtained during the task itself and during test contractions, respectively;
LPD = local perceived discomfort, RPE = rating of perceived exertion, and PPT = pressure pain threshold; number between brackets indicates the applied number of scale units;
EMG amplitude is expressed by the averaged rectified value (ARV) or the root mean square (RMS). MPF = Mean or median power frequency

Discussion

Objective signs of fatigue

Shoulder fatigue is of particular importance in ergonomics. Shoulder disorders are among the most prevalent work-related musculoskeletal disorders (Walker-Bone and Cooper 2005), while local muscle fatigue is assumed to be a main contributor, particularly when it cumulative and adequate recovery is not possible (Sommerich et al. 1993). Moreover, a detrimental effect of fatigue on task performance is plausible in many working areas. Prevention of fatigue should thus be aimed for and any objective assessment of fatigue may help to define and organize the work such that fatigue remains acceptably low. However, the potential of measuring fatigue in realistic low-force work tasks has not been systematically addressed and clarified. This review shows that EMG manifestations of muscle fatigue in the trapezius muscle do appear in low-force activities: in six out of thirteen studies a significant decrease in the EMG power frequency was accompanied by an amplitude increase; the other seven studies showed none or only one of these changes. The lack of a positive result in about half of the studies could be due to a lack of statistical power. However, comparing the number of participants between the studies finding objective signs of fatigue vs. the studies not finding this result, no differences were observed. The same holds for the duration of the task under investigation: the duration was not different between the studies showing manifestations of fatigue and not doing so (see Figure 3-1a and b). Another suggestion could be that fatigue-related changes in muscle activation become less predictable under less constraining conditions due to more confounding factors. When considering the way the included studies were structured and designed, no evidence was found supporting this suggestion. These considerations lead to the conclusion that objective signs of fatigue in the shoulder region are present in at least some of the realistic low-force work tasks.

The question thus arises as to what the determinants of fatigue development in these tasks could be. A potential determinant could be gender of the subject groups. In overhead assembly work, females were observed to exhibit longer endurance times, delayed reports of discomfort and slower declines in strength compared to males (Nussbaum et al. 2001). However, comparing the studies with and without fatigue signs, no evidence was found for a gender effect. Another possible determinant could be the intensity of the work task. Figure 3-1c presents the median amplitude levels of the trapezius activation expressed as a percentage of the maximum for the various studies. For studies not reporting this value, an estimated value is shown. Based on Westgaard et al. (1996) and Thorn et al. (2007), a value of 7%MVC was applied for typing on a keyboard (for the study of Kleine et al. 1999) and 8%MVC for computer work using keyboard and mouse (McLean et al. 2000, Seghers et al. 2003a) and a value of 16%MVC for assembly work (Mathiassen and Winkel 1996, Bosch et al. 2007). The median intensity level in the study of Sundelin (1993) was estimated exactly in between the reported median and peak values. The studies of Hostens and Ramon (2005) and Kimura et al. (2007) with unpredictable intensity levels were omitted. From figure 3-1c it appears that the studies with a positive result with regard to the existence of signs of fatigue have a rather high intensity, specifically above the level of 15%MVC. The intensity level in studies showing no objective signs of fatigue are generally lower. Among these latter studies are all three included studies on computer work.

Perceived fatigue

In all studies that report on subjective experiences, the ratings of perceived fatigue or discomfort were found to increase. No constant or decreasing patterns were reported. In two out of the seven studies finding no objective signs of fatigue, the perceived exertion and discomfort was observed to increase from 1 to 2-4 (10-point scale, Christensen 1986) and from 0.5 to 2.2 (9-points, Nakata et al. 1992), respectively. In the studies demonstrating objective signs of fatigue, the reported increases in perceived fatigue, discomfort or exertion show a large range. Bosch et al. (2007) reported an increase in shoulder discomfort from 0.5 to 2 (on a 10-point scale), while Sundelin (1993) reported an increase of the general perceived exertion from 0 to 14 (20-point scale). Apparently, subjective feelings of fatigue are more consistently found compared to objective fatigue manifestations and, thus, perceived fatigue is not in all cases supported by objective findings. In the present authors' view, there might be many psychological influences when performing a given task with potential effect on the perception of fatigue; only part of these might be objectively measurable.

Changes in muscle activation

The changes in the time and frequency domain of the EMG signal during a fatiguing contraction have been extensively studied. In particular, for prolonged static efforts, it is accepted that a simultaneous downward shift of the frequency spectrum and an increase in the signal's amplitude can be considered as an objective sign of fatigue.

Even though the interpretation of the EMG changes is subject to caution (Dimitrova and Dimitrov 2003), it is believed that the frequency decrease represents a decreased conduction velocity along the muscle fibers (e.g. De Luca 1984) and a larger amount of synchronization of motor unit firing in the fatigued muscle (Lippold 1981). A recent study on sustained low-level activity has revealed indications of increased interstitial potassium concentrations in the descending part of the trapezius muscle, possibly underlying the decreased conduction velocity (Rosendal et al. 2004a). The increase in amplitude when the muscle gets fatigued can be understood from the additional recruitment of motor units. These motor units might be required to compensate for the loss of force producing capacity of the already active units (Moritani et al. 1986). It might also be that the increasing amplitude is a direct result from the decreasing frequency content, because of the low-pass filtering characteristics of skin tissue. At a lower frequency content, a larger proportion of the signal would be able to pass, resulting in the measurement of a higher amplitude (Lindstrom et al. 1977). The fatigue-related changes in the EMG signal can be confounded by various factors. The decrease in frequency content could be masked by the additional recruitment of motor units. Since the motor units being additionally recruited are of a larger size (according to the size-principle), an opposite (upward) shift in the frequency spectrum will be expected. Another potential confounder is the temperature. An increasing temperature in the working muscle would lead to a decrease in the EMG amplitude (Petrofsky and Lind 1980), which may mask the increase in amplitude during fatigue. In non-isometric conditions, extra cautions should be raised: changes in muscle forces, muscle length and muscle contraction velocity may affect the fatigue-related spectral and amplitude changes (e.g. Gerdle et al. 1991). It might be that in some studies participants changed their working posture or working technique over time possibly due to fatigue, potentially affecting the load sharing within the measured muscle or between different muscles. The above confounders may have played a role in the various studies that were included in this review, but their effect in terms of direction and size remains unknown. Of special interest are the studies where only one of the expected changes was found. Hostens and Ramon (2005) did find some indication of (temporal) decreases MPF during driving, which were not accompanied by a simultaneous increase in amplitude. Instead, the amplitude was generally found to decrease. One of their explanations for the decreased amplitude was the potentiation of muscle fibers, where for a given stimulus muscles produce more force, making the muscle more efficient per unit impulse (Garner et al. 1989). Nakata et al. (1992), Kleine et al. (1999), Seghers et al. (2003a) and Rolander et al. (2005) found an increase in EMG amplitude without a decrease of the frequency content. Generally, the combination of an increase in amplitude with no frequency shift indicates an increase in force generation without fatigue. Kleine et al. (1999) suggested that the intensity level in the computer task studied was too low for muscle fatigue to develop, whereas the increase in amplitude of the trapezius muscle was associated with a relative elevation of the shoulders during the task. Similarly, Seghers et al. (2003a) assigned the amplitude increase of the right trapezius electromyography during a computer game to an (unobserved) elevation of the right shoulder. Nakata et al. (1992) also concluded that there was no fatigue development in their study and speculated that the increased amplitude might have resulted from a change (which would mean a decrease) in muscle temperature.

Other measures

This review shows that no manifestations of muscle fatigue during realistic working tasks have been reported thus far, at trapezius activation levels below 15%MVC such as computer work. It cannot be answered whether muscle fatigue simply does not occur at these low intensities or any manifestations of muscle fatigue are not detectable given the unfavorable signal-to-noise ratios. It might be that EMG measurement strategies other than the ones applied can increase the discriminative power. For instance, the conduction velocity of the electrical signal along the muscle fibers, which can be deduced when using two-dimensional electrode arrays, seems to be a more direct measure of muscle fatigue than the frequency content and thus temporal fatigue-related changes may be detected more easily. Kimura et al. (2007) did find a decrease in the conduction velocity of 13% in 1 hour and 55 min. in computer work, while the wrist was loaded by an extra 1 kg. The question remains unanswered whether the conduction velocity would change in normal computer work. For potential measures to assess fatigue other than the traditional EMG-based parameters, it is also still questionable whether these would be affected at very low intensities. The obvious search terms were used to find studies investigating shoulder fatigue development on the basis of MMG, blood oxygen saturation and position sense. However, none of the studies fulfilling the criteria involved one of these methods. Effects of fatigue on MMG, blood oxygen saturation and position sense were studied before by, for example, Björklund et al. (2000), Søgaard et al. (2003) and Heiden et al. (2005), but not during prolonged, low-force activities.

Conclusion

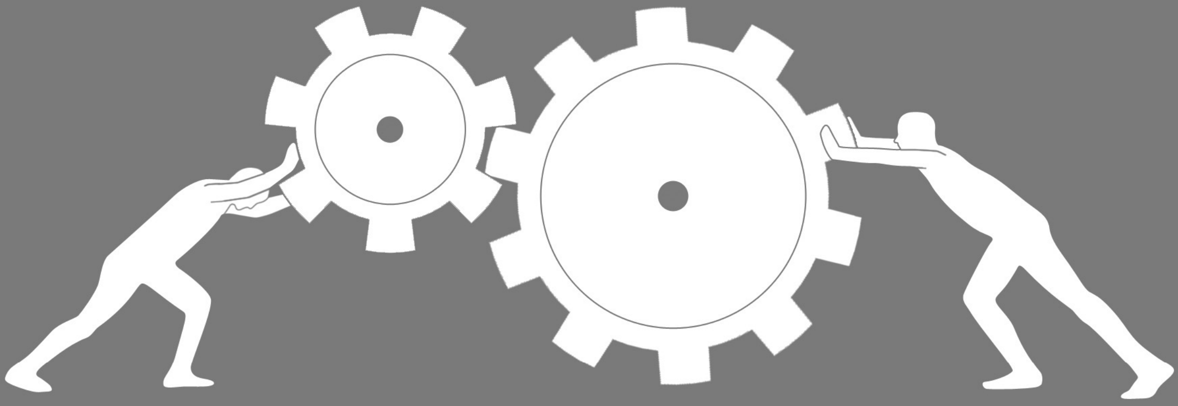
From the studies included in this review, it can be concluded that EMG manifestations of fatigue in the trapezius muscle do appear in low-force activities such as light manual work and assembly when the intensity level is above 15-20%MVC. In the studies finding these objective manifestations of fatigue, the amplitude increases (group averages) ranged across the various studies from 3% to 27%, while the MPF decreases ranged (group averages) from 0.9 to 11%. One can only speculate about the relevance of these findings from the perspective of health. However, the individual fatigue-related changes rather than the group averages may be of more relevance. Several authors mention that the inter-individual variation is large. Sundelin (1993) presented the individual figures, showing amplitude and frequency changes ranging from 18-40% and 2-15%, respectively within the eight out of 12 participants showing evidence of fatigue. Another reason for ergonomists to be interested in fatigue is its potentially negative effect on performance. A negative effect of fatigue on performance has been demonstrated in low-force tasks, but only in isolated, unnatural and constrained tasks (e.g. Huysmans et al. 2008).

For more complex realistic low-force activities, the relation between fatigue-related changes and meaningful performance losses, however, has to the present authors' knowledge not previously been addressed. Without knowing this relationship, it is hard to define the relevance of these review results from the perspective of performance.

Local muscle fatigue seems to occur in some light manual activities and could be considered a risk indicator. However, before having merit as a design and evaluation tool, more information is needed, specifically related to the exact temporal pattern of fatigue development and the relations with shoulder disorder risks and practical measures of performance. This may require fatigue measurement strategies other than the traditional ones applied in the included studies.

Chapter 4

Fatigue during different levels of simulated light manual assembly work



"Electromyographical manifestations of muscle fatigue during different levels of simulated light manual assembly work", Tim Bosch, Michiel de Looze, Idsart Kingma, Bart Visser & Jaap van Dieën
Journal of Electromyography and Kinesiology (2009), 19 (4), e246-e256

Abstract

The purpose of this study was to determine whether objective electromyographical manifestations of muscle fatigue develop in the upper trapezius muscle in two assembly tasks involving contractions of different low-intensity levels (8% and 12 %MVC) and whether these indications of fatigue are homogeneously distributed across different muscle parts. Ten participants performed an assembly task for three hours. EMG was recorded using four pairs of bipolar electrodes over the left and right trapezius muscles during the task itself and during isometric test contractions. Both recordings (during task and test) showed a significant decrease in the mean power frequency (MPF), at both intensity levels while the amplitude remained constant. A regression analysis showed significantly different temporal patterns for the MPF decrease for the two intensities. No differences in manifestations of muscle fatigue development were found between different parts of the muscle. These results indicate that in a highly repetitive low-intensity task, electromyographical manifestations of muscle fatigue can be observed from signals recorded in the task itself. Furthermore, the rate of development of fatigue manifestations was different between the two assembly tasks. This fatigue development appeared to be homogenous across the muscle.

Introduction

Shoulder pain is a serious problem in the working population (Buckle and Devereux 2002). Epidemiological reviews show strong associations between work exposures and shoulder pain (Bongers et al. 2002, Punnet and Gold 2003). Remarkably, elevated risks of developing shoulder pain are not restricted to conditions where internal loads are high (National Research Council and Institute of Medicine 2001). Repetitive manual assembly work is an example of low-intensity work in which risks of shoulder pain are elevated (Hagberg and Wegman 1987, Mathiassen et al. 1993). It is often hypothesized that in this type of work muscle fatigue is a pain initiating factor (Bjelle et al. 1981, Rempel et al. 1992, Takala 2002). Findings of objective signs of fatigue in low-intensity work are quite limited. Changes in the electromyographic activity (a decrease in the mean power frequency and/or an increase in the EMG-amplitude) during standardized voluntary contractions have frequently been used as indicators of muscle fatigue (Bigland-Ritchie and Woods 1984, Merletti et al. 1991). Sundelin and Hagberg (1992) did find an increase in the EMG amplitude and a decrease in the EMG frequency content of the trapezius muscle in a simulated one-hour pick and place task. Others studied a two-hour task (Suurküla and Hägg 1987), a six-hour assembly task (Mathiassen and Winkel 1996) and an eight-hour assembly task (Bosch et al. 2007). In these studies, trends indicating manifestations of fatigue based on EMG parameters were reported, but these were either not statistically tested or only partially significant. In none of these studies, the intensity level of the task was quantified, nor were differences in fatigue development between different levels of low-intensity addressed.

In studies on other muscles than the upper trapezius muscle, manifestations of muscle fatigue due to isolated activities were studied (e.g. Bennie et al. 2002, Dennerlein et al. 2003, Søgaard et al. 2003). Objective signs of manifestations of fatigue were found, but it remains questionable whether these results can be extrapolated to fatigue development in the shoulder muscles in more natural tasks. Generally, it seems that changes in the MPF and amplitude of the EMG signal are less consistent for prolonged low-level dynamic contractions than for high-force contractions.

In most of the above-mentioned studies, EMG signals were recorded during some type of isometric reference contraction, clearly separated from the low-intensity activity under study. These isometric test contractions allow the recording of stationary signals that are likely to be produced by the same pool of motor units (MU) in every measurement. In contrast, direct EMG measurements during the actual repetitive low-intensity work may lead to erroneous interpretations as factors like muscle length, muscle-electrode distance and movement velocity are hard to control (Madeleine et al. 2001). On the other hand, test contractions may also have disadvantages. It can for example not be ascertained that a reference contraction is representative of the motor unit recruitment during the real task (Søgaard et al. 2003, Blangsted et al. 2005). Other disadvantages are the disruption of the work process and the fact that the test contractions themselves might have an effect on fatigue development. From these perspectives, it is worth studying whether in short-cyclic activities extended periods of EMG recording during the work itself would yield similar results compared to EMG recordings during test contractions.

Another methodological issue concerns the common use of a single standard electrode position for the upper trapezius muscle. According to Hermens et al. (2000), approximately midway between the clavicle and the scapula is the best position to obtain an estimate of the overall muscle activity. It has been reported that some cat muscles (English and Weeks 1984, Hensbergen and Kernell 1992) and the human masseter (Blanksma et al. 1992), biceps brachii (Gielen and Denier van der Gon 1990) and pectoralis major muscles (Paton and Brown 1994) are functionally subdivided. Moreover multiple surface EMG recordings have indicated that the trapezius muscle, which inserts onto the acromion and the lateral parts of the clavicle and scapula, may also be divided into functionally different compartments (Jensen and Westgaard 1997, Jensen and Westgaard 1995, Holtermann et al. 2005). This may indicate that fatigue not necessarily develops in a homogenous way.

In the current study, we investigated the development of manifestations of fatigue in the shoulder region during a three-hour repetitive assembly task at two low-intensity levels. To this end we recorded the upper trapezius EMG during the assembly task and during separate isometric test contractions.

Our research questions were:

- Can objective manifestations of muscle fatigue be obtained from EMG recordings during a standardized three-hour light assembly task and can differences between two different levels of low-intensity work be detected?
- Do fatigue indicators based on EMG differ between EMG recorded during the assembly task and EMG obtained during isometric test contractions?
- Do manifestations of fatigue in the upper trapezius muscle develop in a homogenous way?

Methods

Participants

Ten healthy participants volunteered to participate in the study (five males and five females, mean (SD) age was 32.5 (15.4) years, mean body mass 76.6 (8.1) kg and mean height 177 (8.6) cm). All participants were right-handed. None of the participants reported any history of musculoskeletal complaints in the previous year. Participants were not exposed to excessive exercise of the arms on their jobs or in their leisure time before the test period. The study was approved by the local Ethics Committee.

Procedure

The participants had to perform a three-hour simulated assembly work task at two intensity levels. Nine participants were measured on two consecutive days, while one of the participants was measured on two days, spread over a two-weeks time period. The order of the two conditions was randomly assigned to the participants. To become familiar with the experimental equipment and procedures a training session was performed before the start of the experiment. All sessions were performed in a laboratory at a temperature of 22 °C.

Task

The task was based on a realistic assembly task described by de Looze et al. (2005). Boxes with blocks were placed on the left and right side of the participant. The task consisted of constructing and taking apart a small tower of eight blocks. Participants constructed and broke down a tower in front of them with a cycle time of thirty seconds. Both hands were used in alternating order and one block was picked-up at a time. After completing a tower, participants put it in a box in front of them. The task had a fixed order which was strictly controlled. The participants were comfortably seated in a chair with the back vertical and the feet in full contact with the floor or with a footrest.

In the first condition (Low-condition), the table height was individually adjusted so the elbow was flexed slightly more than 90° and the palms of the hands were just above the table. In the second condition (High-condition) table height was increased by 10 cm, the box height of the parts was increased by 15 cm and the front boxes were placed 35 cm further away. In both conditions, participants were not allowed to lean on the table during the tasks.

Maximal voluntary contractions

At the start of each experimental day, three maximal voluntary contractions (MVC) of the left and right m. trapezius pars decendens were performed. The participant was seated on a chair with the knees 90° flexed and the arms hanging vertically. Adjustable straps were positioned over the top of both shoulders, while the participants stretched their back maximally. This was controlled by asking the participants to extend the head against a metal pin placed slightly above the head. The length of the straps was registered in order to reproduce the strap adjustments throughout the experimental days. Participants were asked to perform maximal isometric shoulder elevation against the resistance applied by the straps for four seconds. The straps were connected to strain-gauge force transducers to obtain the maximal voluntary force (MVF) applied to the straps. Using the strain gauge signals, the one-second window with the highest force level over the three trials was considered to be the MVF. From the same trials, the maximal voluntary excitation (MVE) of the trapezius muscles was determined using the EMG signals. Each trial was followed by a rest period of at least one minute.

Measurements

EMG signals were recorded from the descending part of the upper trapezius muscle by using bipolar Ag/AgCl surface electrodes (Blue Sensor, Medicotest). Four pairs of bipolar electrodes were placed on both the right and left upper trapezius muscle. A standard electrode location was defined as described by Hermens et al. (2000). Figure 4-1 illustrates the electrode locations. The reference electrode was placed over the C7 spinous process. The electrode positions were marked with a waterproof pencil, in order to place the electrodes at the exact same position in both conditions. EMG signals were amplified 20 times (Porti- 17TM, TMS, Enschede, The Netherlands, input impedance $>10^{12}$ Ώ, CMRR >90 dB), band-pass filtered (10–400 Hz) and A–D converted (22-bits) at a sample rate of 1000 Hz. EMG was recorded every other 2.5 minutes (5 subsequent cycles*30 seconds = 1 trial) during the task performance. Furthermore an isometric test contraction, consisting of thirty seconds shoulder elevation, was performed every fifteen minutes. Test contractions were performed with the same body posture and set-up as the MVC trials with an intensity of 5% MVF. Visual feedback of actual force level was given on a computer screen.

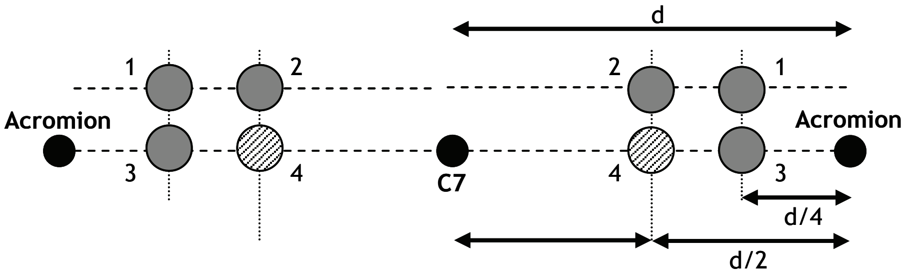


Figure 4-1. *Outline of the electrode locations. Electrode pairs 3 and 4 were aligned to the line between C7 and acromion. The standard electrode location (4) was defined as half of the distance (d/2) between C7 and acromion. Electrode pair 3 was placed at a fourth (d/4) of this distance. Electrode pairs 1 and 2 were placed ventrally at a distance of 1 cm.*

Data analysis and statistics

The mean amplitude was determined by averaging the band pass filtered (10-400 Hz), rectified and normalised EMG signal over 5 cycles (2.5 min). The Mean Power Frequency (MPF) was calculated using a sliding window technique with a step size of 500 samples and a window size of 5000 samples. MPF values were calculated per window and averaged over one trial, resulting in one MPF value for each trial. Consequently, 36 MPF and mean amplitude samples were obtained during the task and 12 samples were obtained during the isometric test contractions.

Plots were composed for the standard electrode location in both conditions to consider the changes in EMG amplitude and spectrum simultaneously (Joint Analysis of EMG Spectrum and Amplitude – JASA; Luttmann et al. 1996). A simultaneous increase of the EMG amplitude and a decrease of the MPF is generally considered indicative of fatigue (Basmajean and De Luca 1985).

A second order regression line was fitted through the MPF and mean amplitude samples for the standard electrode locations. A second order fit was used because non-linearity was expected (Krogh-Lund and Jensen 1985). The coefficients and intercepts of the regression equations for the standard electrode locations were analyzed using repeated-measures ANOVA (ANOVA 1, with independent variables condition (2) and side (2)).

To test whether similar conclusions would be obtained using a simplified procedure, the EMG data obtained at the start and end of both conditions were analyzed with a

repeated-measures analysis of variance (ANOVA 2, with independent variables time (2), condition (2) and side (2)).
To test whether EMG changes differed between electrode locations, second order regression lines were fitted through each of the time patterns of all the electrode locations. Subsequently, the coefficients of these regression equations were tested using an ANOVA (ANOVA 3) with the independent variables condition (2), side (2) and location (4). The p-value was based on degrees of freedom corrected with Greenhouse–Geisser's epsilon to compensate for the effects of violations of the sphericity assumption (Twisk 2003). Bonferonni-corrected t-tests were used as post-hoc test for comparisons of means.

Results

Development of manifestations of muscle fatigue

It was our intention to impose conditions with two different intensities of muscle activity of the trapezius. It appeared from the initial amplitude (intercept) that the intensity differed significantly between conditions ($p=0.001$). The initial amplitude was 8.6 (5.1) in the Low- and 12.5 (5.2) %MVE in the High-condition.

The plots presented in figure 4-2 show the MPF and amplitude changes for both conditions. In the High- and Low-condition, the majority of the participants showed an increase in amplitude and a decrease in MPF during the task and the test contractions. The mean coefficients of the regression lines fitted through the individual data series are shown in table 4-1. These data were analyzed using ANOVA 1 (Table 4-2). The change in amplitude during the three-hour assembly task did not significantly differ between the High- and Low-condition. In contrast to the amplitude, both regression coefficients for the MPF differed significantly between conditions. The linear coefficient ($p=0.027$) as well as the quadratic coefficient ($p=0.020$) were lower for the High-condition than for the Low-condition. The coefficients of the MPF obtained during the test contractions did not differ significantly between conditions.

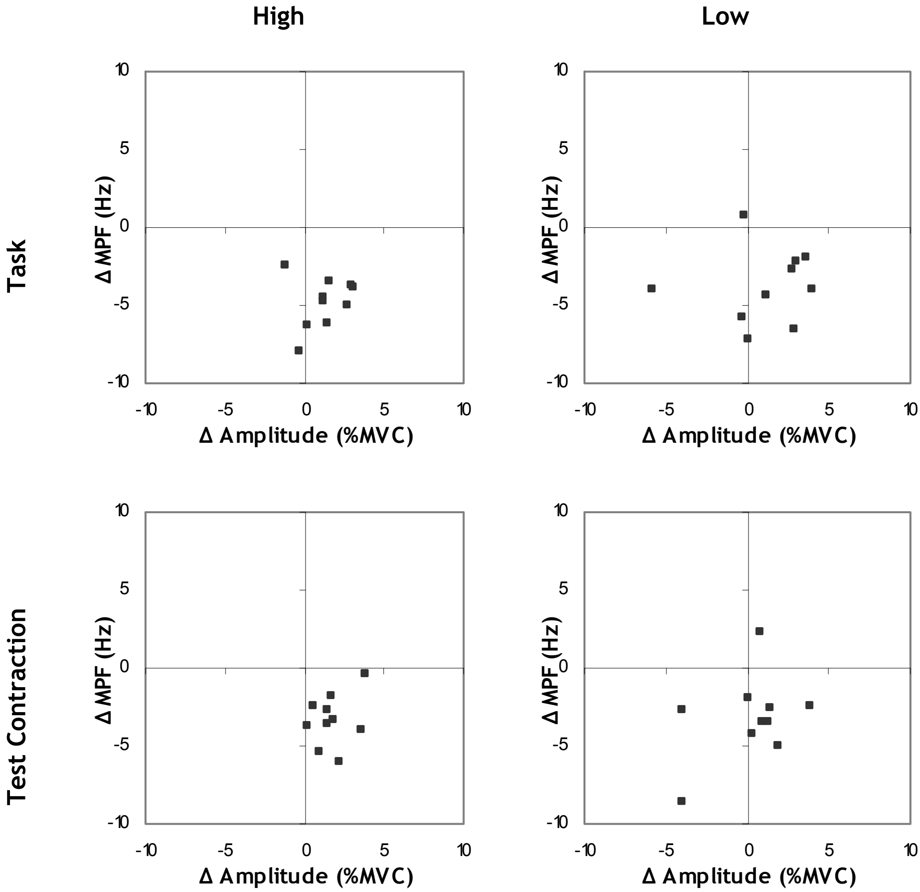


Figure 4-2. *Two dimensional plots of 10 participants in the High-condition (left) and the Low-condition (right) for the amplitude and MPF changes during the task (top) and isometric test contraction (bottom) for the standard electrode location. The differences between the MPF and amplitude values at the start (t1) and end (t36 or t12) were estimated using the second order regression equations.*

Table 4-1. *Mean intercept and coefficients (SD) for the task and test contraction.*

Condition/Side		**Task**			**Test contraction**		
Amplitude		**Intercept**	**Coefficient 1**	**Coefficient 2**	**Intercept**	**Coefficient 1**	**Coefficient 2**
High/Left	Location 1	13.0 (4.2)	0.04 (0.09)	-0.0005 (0.002)	13.4 (4.8)	0.73 (1.32)	-0.0412 (0.102)
	Location 2	12.5 (3.6)	0.04 (0.12)	-0.0006 (0.003)	13.2 (3.6)	0.59 (1.08)	-0.031 (0.083)
	Location 3	12.8 (4.8)	0.04 (0.12)	-0.0004 (0.003)	13.9 (5.0)	0.63 (0.49)	-0.0293 (0.035)
	Location 4	13.1 (5.2)	0.05 (0.09)	-0.0008 (0.002)	12.9 (3.9)	0.70 (0.73)	-0.0387 (0.054)
High/Right	Location 1	11.4 (5.4)	0.07 (0.10)	-0.0009 (0.003)	10.8 (4.7)	0.51 (1.05)	-0.0373 (0.076)
	Location 2	12.0 (6.4)	0.05 (0.13)	-0.0003 (0.003)	11.2 (5.2)	0.40 (1.05)	-0.0267 (0.074)
	Location 3	11.3 (5.2)	0.06 (0.14)	-0.0004 (0.003)	12.0 (4.6)	0.66 (0.75)	-0.0424 (0.055)
	Location 4	12.1 (5.6)	0.10 (0.13)	-0.0014 (0.003)	11.2 (4.7)	0.63 (0.69)	-0.0386 (0.054)
Low/Left	Location 1	8.9 (4.9)	0.00 (0.24)	0.0007 (0.004)	14.1 (4.4)	0.51 (0.94)	-0.031 (0.074)
	Location 2	9.6 (5.3)	0.01 (0.22)	0.0006 (0.004)	14.5 (4.4)	0.47 (0.91)	-0.0267 (0.068)
	Location 3	8.5 (4.2)	0.01 (0.17)	0.0004 (0.003)	16.1 (4.7)	0.04 (1.55)	0.0008 (0.095)
	Location 4	9.4 (4.5)	0.01 (0.19)	0.0003 (0.004)	15.5 (4.7)	0.11 (1.29)	-0.0056 (0.080)
Low/Right	Location 1	7.0 (4.0)	0.03 (0.13)	0.0000 (0.002)	12.8 (4.9)	-0.16 (0.9)	0.0112 (0.060)
	Location 2	8.6 (7.7)	0.03 (0.16)	0.0003 (0.002)	14.2 (9.5)	0.01 (1.01)	0.0001 (0.067)
	Location 3	7.5 (5.0)	0.03 (0.16)	0.0001 (0.002)	14.8 (5.6)	-0.04 (0.94)	0.0065 (0.064)
	Location 4	8.8 (6.2)	0.04 (0.15)	0.0000 (0.002)	14.6 (6.1)	-0.08 (0.76)	0.0074 (0.052)

Table 4-1. *Continued*

Condition/Side		Task			Test contraction		
MPF		Intercept	Coefficient 1	Coefficient 2	Intercept	Coefficient 1	Coefficient 2
High/Left	Location 1	56.5 (6.9)	-0.34 (0.17)	0.0055 (0.003)	54.7 (5.4)	-0.84 (0.47)	0.0462 (0.046)
	Location 2	53.7 (4.2)	-0.27 (0.10)	0.0038 (0.003)	54.7 (4.8)	-0.92 (0.45)	0.0483 (0.036)
	Location 3	55.3 (4.6)	-0.27 (0.12)	0.0039 (0.003)	55.8 (5.7)	-0.75 (0.54)	0.0431 (0.048)
	Location 4	57.6 (5.2)	-0.34 (0.16)	0.0051 (0.003)	59.3 (7.0)	-0.66 (0.33)	0.0282 (0.031)
High/Right	Location 1	6.7 (6.7)	-0.30 (0.21)	0.0045 (0.004)	56.5 (4.8)	-1.08 (0.87)	0.0556 (0.071)
	Location 2	56.3 (5.3)	-0.29 (0.13)	0.0043 (0.003)	56.1 (6.9)	-1.04 (0.98)	0.0561 (0.074)
	Location 3	55.1 (4.0)	-0.27 (0.20)	0.0043 (0.004)	56.4 (6.1)	-0.55 (0.46)	0.0220 (0.036)
	Location 4	58.9 (5.0)	-0.30 (0.13)	0.0046 (0.003)	59.6 (6.8)	-0.70 (0.34)	0.0296 (0.030)
Low/Left	Location 1	57.5 (6.8)	-0.29 (0.24)	0.0036 (0.005)	59.7 (6.3)	-0.76 (0.99)	0.0336 (0.068)
	Location 2	48.9 (5.8)	-0.20 (0.25)	0.0022 (0.005)	54.6 (5.2)	-0.57 (0.67)	0.0247 (0.054)
	Location 3	53.2 (7.1)	-0.22 (0.17)	0.0029 (0.003)	58.2 (6.5)	-0.85 (1.17)	0.0428 (0.080)
	Location 4	54.4 (6.3)	-0.21 (0.20)	0.0025 (0.004)	61.3 (6.6)	-0.68 (0.54)	0.0346 (0.044)
Low/Right	Location 1	55.9 (7.4)	-0.23 (0.22)	0.0026 (0.004)	58.1 (5.9)	-0.89 (0.79)	0.0366 (0.054)
	Location 2	51.1 (4.3)	-0.13 (0.21)	0.0012 (0.004)	57.0 (7.2)	-0.69 (0.78)	0.0267 (0.051)
	Location 3	51.7 (3.7)	-0.15 (0.22)	0.0017 (0.004)	58.8 (6.0)	-0.70 (1.01)	0.0323 (0.070)
	Location 4	54.7 (6.2)	-0.14 (0.24)	0.0011 (0.005)	62.9 (8.6)	-0.90 (1.23)	0.0416 (0.077)

Table 4-2*.* *Results of ANOVA 1 on the coefficients of a second order regression equation of time versus amplitude and MPF for the standard electrode location during the task and test contractions.*

		Task						**Test contraction**					
ANOVA 1		**Amplitude**			**MPF**			**Amplitude**			**MPF**		
		df	F	p	df	F	p	df	F	p	df	F	p
Intercept	Condition (high, low)	1	26.8	**0.001**	1	16.3	**0.003**	1	10.4	**0.011**	1	5.3	**0.047**
	Side (left, right)	1	0.2	0.658	1	0.5	0.495	1	1.4	0.267	1	0.9	0.368
	Side * condition	1	0.1	0.719	1	1.6	0.242	1	0.2	0.691	1	0.6	0.454
Coefficient 1	Condition (high, low)	1	1.7	0.231	1	7.0	**0.027**	1	4.4	0.065	1	0.2	0.686
	Side (left, right)	1	6.2	**0.035**	1	2.8	0.128	1	0.5	0.485	1	0.5	0.512
	Side * condition	1	0.3	0.610	1	0.7	0.443	1	0.04	0.851	1	0.2	0.663
Coefficient 2	Condition (high, low)	1	2.6	0.144	1	7.9	**0.020**	1	3.5	0.096	1	0.2	0.661
	Side (left, right)	1	0.8	0.393	1	1.7	0.220	1	0.2	0.643	1	0.1	0.740
	Side * condition	1	0.1	0.814	1	0.9	0.374	1	0.1	0.749	1	0.1	0.817

Independent variables: condition (high/low) and side (left/right).

Presented degrees of freedom (df), F-values and p-values. Significant results ($p<0.05$) are marked bold.

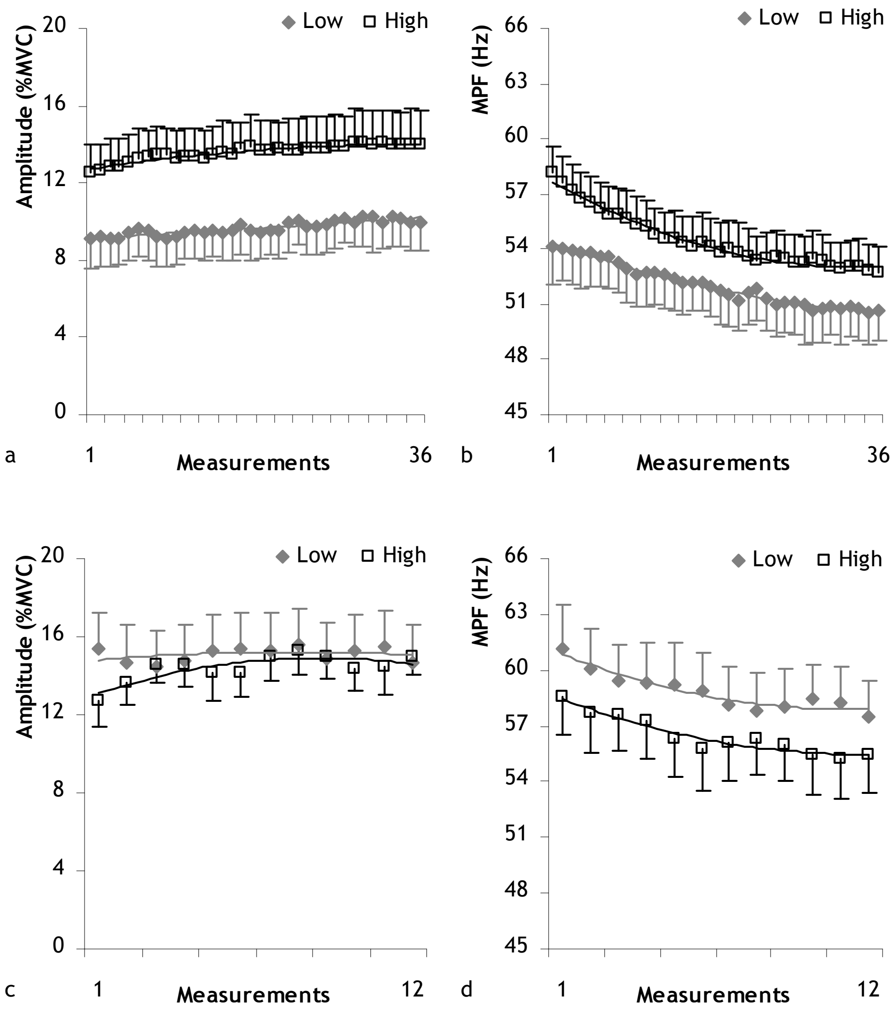


Figure 4-3. *Change of amplitude and MPF during the task and the isometric test contraction.*

a. *Upper left: Mean amplitude task,* ***b***. *Upper right: MPF task,* ***c***. *Lower left: Mean amplitude isometric test contraction,* ***d***. *Lower right: MPF isometric test contraction. The values are averaged over 10 participants and error bars indicate the standard error of the mean.*

***Table 4-3**. Mean amplitude and MPF values (SD) for start and end measurements of the task and test contraction*

Condition/Side	**Task**		**Test contraction**	
	Start	**End**	**Start**	**End**
Amplitude				
High-Left	11.9 (5.4)	14.1 (6.9)	11.6 (4.8)	13.6 (3.9)
High-Right	13.3 (5.6)	13.9 (6.0)	13.3 (4.6)	16.4 (3.5)
Low-Left	8.6 (5.9)	9.9 (6.5)	14.7 (4.8)	14.1 (6.3)
Low-Right	9.3 (4.7)	10.1 (4.0)	16.3 (4.7)	15.3 (5.9)
MPF				
High-Left	59.1 (5.1)	53.7 (5.6)	59.0 (6.9)	55.5 (7.8)
High-Right	58.0 (5.3)	51.7 (4.7)	59.2 (6.8)	55.5 (6.2)
Low-Left	54.3 (6.7)	51.2 (5.8)	62.3 (8.4)	57.4 (6.7)
Low-Right	54.0 (6.5)	50.1 (5.0)	61.0 (7.0)	57.6 (5.2)

The mean values of the amplitude and MPF at the start and end of the conditions are shown in table 4-3. The differences between the real initial and final measurements during the task and the test contractions were tested in ANOVA 2 (Table 4-4). For the task as well as the test contraction, the MPF decreased significantly over time (Figure 4-3b and 4-3d). Considering the significant interaction between time and condition for the task, this decrease was larger for the High-condition compared to the Low-condition. The amplitude showed no significant changes (Figure 4-3a and 4-3c).

Additional electrode locations

Figure 4-4 shows a typical example of the development of the mean amplitude and MPF for four different electrode locations on the left upper trapezius muscle. At first sight, the patterns for the different locations are more or less similar. To determine whether manifestations of muscle fatigue showed a homogenous development over the muscle the coefficients of the regression lines fitted through the individual data series for four different muscle locations on both sides were analyzed using ANOVA 3 (Table 4-5). There was no significant effect of location, nor a significant interaction between condition and location for the linear and quadratic coefficients. The mean amplitude of the isometric test contraction showed a significant interaction between condition and location for the linear coefficient (p=0.017) and a tendency towards significance (p=0.067) for the quadratic coefficient. Post-hoc testing (Bonferonni-corrected t-test) did not show significant differences between the locations.

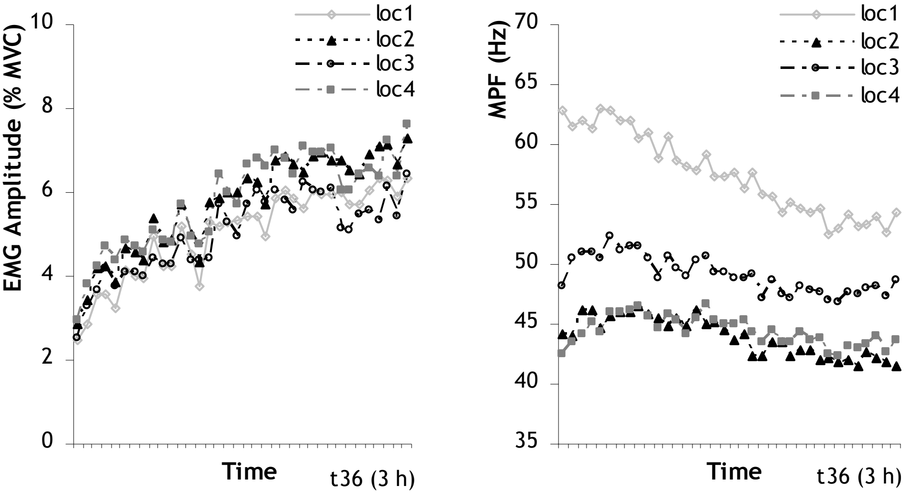


Figure 4-4*. Typical example of development of the amplitude and MPF over three hours for four different electrode locations on the left upper trapezius during the Low-condition.*

Table 4-4. Results of ANOVA 2 on the amplitude and MPF at the standard electrode location for the task and isometric test contraction are presented.

	Task						**Test Contraction**					
ANOVA 2	**Amplitude**			**MPF**			**Amplitude**			**MPF**		
	df	F	p	df	F	p	df	F	p	df	F	p
Time (start, end)	1	2.6	0.139	1	38.1	**<0.001**	1	3.4	0.097	1	50.4	**<0.001**
Condition (high, low)	1	55	**<0.001**	1	22.4	**0.001**	1	4.7	0.058	1	5.2	**0.049**
Side (left, right)	1	0.0	0.876	1	1.6	0.239	1	0.4	0.568	1	0.5	0.495
Time * Condition	1	0.1	0.713	1	9.5	**0.013**	1	3.2	0.107	1	0.2	0.646
Time* Side	1	7.5	**0.023**	1	2.4	0.152	1	0.1	0.753	1	1.0	0.334
Condition * Side	1	0.0	0.876	1	1.6	0.239	1	0.4	0.568	1	0.5	0.495
Side * Time * Condition	1	2.6	0.139	1	0.0	0.991	1	0.3	0.62	1	1.6	0.233

Independent variables were time (start/end), condition (high/low) and side (left/right).

Presented degrees of freedom (df), F-values and p-values. Significant results ($p<0.05$) are marked bold.

***Table 4-5**. Results of ANOVA 3 on coefficients of a second order regression equation on time versus amplitude and MPF during the task and test contractions for the multiple electrode locations.*

		Task						**Test contraction**					
ANOVA 3		**Amplitude**			**MPF**			**Amplitude**			**MPF**		
		df	F	p	df	F	p	df	F	p	df	F	p
Intercept	Condition (high, low)	1	27.7	**0.001**	1	12.4	**0.006**	1	7.3	**0.024**	1	4.1	0.074
	Side (left, right)	1	0.7	0.411	1	0.2	0.669	1	1.7	0.222	1	0.7	0.418
	Location (loc 1 – 4)	2	0.9	0.427	1	2.3	0.149	3	1.2	0.323	2	4.4	**0.030**
	Condition * Side	1	0.0	0.955	1	2.7	0.136	1	0.7	0.442	1	0.1	0.774
	Condition * Location	2	1.0	0.386	2	4.5	**0.037**	2	0.9	0.403	2	3.5	0.059
	Side * Location	2	0.5	0.615	2	1.7	0.214	2	0.2	0.78	2	0.5	0.618
	Condition * Side * Location	1	0.3	0.703	2	0.2	0.822	2	0.1	0.878	2	1.7	0.219

Table 4-5. *Continued.*

		Task						Test contraction					
ANOVA 3		**Amplitude**			**MPF**			**Amplitude**			**MPF**		
		df	F	p	df	F	p	df	F	p	df	F	p
Coefficient 1	Condition (high, low)	1	1.1	0.331	1	5.0	0.052	1	2.5	0.147	1	0.1	0.813
	Side (left, right)	1	2.5	0.15	1	1.4	0.264	1	1.7	0.223	1	0.3	0.612
	Location (loc 1 – 4)	2	1.2	0.341	2	1.6	0.232	1	0.1	0.817	2	0.8	0.445
	Condition * Side	1	0.0	0.868	1	2.1	0.179	1	0.3	0.604	1	0.0	0.927
	Condition * Location	2	1.0	0.383	2	1.7	0.213	2	5.2	**0.017**	2	1.9	0.185
	Side * Location	2	0.7	0.534	2	0.2	0.841	1	1.2	0.319	2	1.4	0.282
	Condition * Side * Location	2	0.2	0.797	2	0.6	0.56	2	0.7	0.519	2	0.2	0.871

Table 4-5. *Continued.*

		Task						Test contraction					
ANOVA 3		**Amplitude**			**MPF**			**Amplitude**			**MPF**		
		df	F	p	df	F	p	df	F	p	df	F	p
Coefficient 2	Condition (high, low)	1	1.6	0.240	1	5.3	**0.047**	1	1.9	0.202	1	0.1	0.728
	Side (left, right)	1	0.3	0.608	1	0.8	0.403	1	0.5	0.488	1	0.0	0.990
	Location (loc 1 – 4)	2	1.7	0.212	2	1.6	0.229	1	0.2	0.697	2	0.5	0.603
	Condition * Side	1	0.0	0.859	1	1.5	0.254	1	0.6	0.473	1	0.0	0.958
	Condition * Location	2	0.7	0.511	2	1.2	0.315	2	3.2	0.067	2	2.1	0.153
	Side * Location	2	1.6	0.235	2	0.3	0.789	1	1.0	0.364	2	1.1	0.371
	Condition * Side * Location	2	0.4	0.619	2	0.7	0.507	2	0.7	0.516	2	0.2	0.847

Independent variables: condition (high/low), side (left/right) and location (1- 4).

Presented degrees of freedom (df), F-values and p-values. Significant results (p<0.05) are marked bold.

Discussion

In the current study, the development of electromyographical manifestations of fatigue in the upper trapezius muscle were investigated using EMG recordings during a repetitive assembly task at two low-force levels. According to Hagberg and Ericson (1982) the MPF intercept of the High-condition was higher than the MPF intercept of the Low-condition.

Figure 4-2 showed that over a period of three hours most of the participants showed a combination of an increase of the EMG amplitude and a decrease of the MPF. The combination of these changes has been interpreted as a manifestation of muscle fatigue (Basmajian and De Luca 1985, Montes Molina et al. 1997).

At the group level, the statistical analysis showed a significant decrease of the MPF over time in both conditions. Furthermore, this decrease was larger in the High-condition compared to the Low-condition. The changes in the frequency content have usually been explained as stemming from changes in conduction velocities and from synchronization of active motor units (Chaffin 1973, De Luca 1984, Fallentin et al. 1993). In contrast to the MPF decrease, the increase of the mean amplitude was not significant in either of the conditions as most clearly illustrated in ANOVA 2. We can only speculate on some explanations for this relatively constant amplitude. Firstly, the active motor units, while fatigued, may still able to sustain the required low forces, hence requiring no or minimal recruitment of additional motor units. Secondly, during the effort, tissue temperature may increase due to metabolic changes and cause a decrease in amplitude and an increase in MPF (Winkel and Jørgensen 1991). As a consequence of the temperature increase the MPF decrease might even be underestimated and the activation increase required due to fatigue might be hidden. Finally, the amplitude may have been affected by a reduction of required forces as a result of improved working technique. This feasible change in working technique may have contributed to an MPF decrease.

The development of electromyographical manifestations of fatigue in the trapezius muscle has been studied extensively during low-force isometric contractions (e.g. Jørgensen et al. 1988, Madeleine et al. 2002). However, the development of electromyographical manifestations of fatigue during prolonged and more realistic (assembly) tasks have been reported only in a few studies (e.g. Mathiassen and Winkel 1996, Bosch et al. 2007). These studies also showed electromyographic indications of muscle fatigue over the course of a working day. The definition of the task and conditions in the current study were based on a previous field study (de Looze et al. 2005). This study showed that even in this low-intensity task lowering the working height had a positive effect on productivity and self-reported discomfort. The question remained whether objective indicators of muscle fatigue could be detected during this type of work. In the current study these objective indicators were investigated. The sensitivity of electromyographical fatigue manifestations to different intensity levels was previously studied by Krogh-Lund and Jensen (1985) during intermittent isometric contractions of the triceps brachii (15 vs. 20%MVC). The 20%MVC condition showed an increase of amplitude accompanied by a decrease of mean frequency, while at the lower contraction level neither of the EMG parameters did change significantly over 7 hours of work. In contrast, we found a decrease in MPF for the High-condition as well as the Low-condition.

We also studied the detailed temporal development of electromyographical fatigue manifestations. The decrease of the MPF showed a different pattern between conditions. In the High-condition, the MPF showed a non-linear decrease, while it showed a more linear decrease in the Low-condition (see Figure 4-3b). Consistent with our results in the High-condition, Krogh-Lund and Jensen (1985) showed that during an intermittent isometric contraction (20%MVC) the most rapid changes took place over the first 2-3 hours of work.

For field application of the methods studied, a reduction of the number of measurements is preferable because measurements might disrupt the (production) process. Using samples obtained at the start and end of the task only did not yield different main conclusions than using all 36 samples. However, having more measurements provided more detailed information on the temporal pattern of the development of fatigue. Our results indicated a non-linear development. This may be important in practical situations to apply temporal interventions (e.g. job rotation, work-rest schemes), correctly.

Under dynamic conditions (i.e. our assembly task), factors that can hardly be controlled (such as muscle length, muscle-electrode distance and movement velocity) may lead to erroneous interpretation of the EMG signals (Madeleine et al. 2001). Therefore, previous studies introduced isometric test contractions to be performed at specific time points during the dynamic task to study the development of fatigue (Suurküla and Hägg 1987, Mathiassen and Winkel 1996, Bennie et al. 2002, Søgaard et al. 2003, Bosch et al. 2007). An isometric test contraction allows the recording of stationary signals that are likely to be produced by the same pool of motor units in every measurement. On the other hand, it is not known whether a test contraction is representative of the motor unit recruitment during the real assembly task (Søgaard et al. 2003, Blangsted et al. 2005).

In this study, EMG was obtained directly from the task as well as from standardized isometric test contractions. It appeared that manifestations of fatigue in EMG recordings were more pronounced during the task than during the isometric test contractions. The intensity level of our test contraction could explain this. The test contraction was controlled by force feedback (5 %MVF). This level was chosen based on pilot testing. However, after analyzing the EMG signals it appeared that the test contraction was performed at an average level of 14 %MVE, which exceeds the level of intensity of the dynamic tasks (8.7% in the Low- and 12.8 % in the High-condition). Søgaard et al. (2003) recommended the use of test contractions at a lower level of activity than the task itself to ensure that the MU's that have most likely not been participating during the task are not involved in the test contraction. These higher threshold MU's could actually mask any indications of fatigue in the exercised part of the motor unit pool.
The errors that might occur during dynamic contractions are likely to have been minimized in our assembly task by using a highly standardized short-cyclic work task. Furthermore, sampling five work cycles, data derived from the dynamic EMG signal should be relatively independent of these errors as a result of averaging (Roy et al. 1998, Nussbaum 2001). In addition, a recent study by Farina showed that the muscle movement of the upper trapezius muscle is negligible for a large range of arm positions (Farina et al. 2002). The above suggests that electromyographical manifestations of muscle fatigue in the upper trapezius muscle can be studied from EMG signals directly recorded from the dynamic task, in case this task is standardized and highly repetitive.

We also studied differences in manifestations of fatigue development in different parts of the muscle, by including additional electrode sites in our analysis. We found that the MPF decreased significantly at all four electrode locations and that this decrease did not significantly differ among electrode locations in the task nor in the test contraction. The amplitude did not change at any location during the task. However, during the test contraction a subtle difference between muscle parts was found for the mean amplitude.
Previous studies indicated that some muscles are most likely subdivided in so called neuromuscular compartments (Mathiassen and Winkel 1990, Jensen and Westgaard

1995, Holtermann et al. 2005). These compartments are thought to be controlled in part independently by the central nervous system and to have distinct biomechanical functions (Segal 1992, Lim et al. 1999). Furthermore, topographical differences in trapezius activation in a dynamic task were shown by Jensen and Westgaard (1997). However, this does not necessarily imply that fatigue develops in a heterogeneous way during prolonged dynamic loading. Differences in the development of muscle fatigue between parts of the trapezius descendens muscle were shown by Mathiassen and Aminoff (1997) during a low-force isometric contraction of 15 minutes. In contrast, our results seem to indicate that during a non-isometric assembly task indications of fatigue develop in a homogenous way. These results might be influenced by the nature of the task. Assembly tasks with a more unilateral loading of specific parts of the trapezius muscle may result in a different fatigue development for different parts of the muscle. In this study, the placement of additional electrodes did not give more information. However, the electrodes in the current study were not aligned along a linear grid. Fixed positions were used but small variations between locations could not be excluded. A reliable estimation of conduction velocity was therefore not feasible. Multi-electrode arrays (one or two dimensional) can provide additional information from estimates of conduction velocities (Merletti et al. 2003), or identification of single MU's (e.g. Merletti et al. 1999). Despite the duration (three hours) of the assembly task in the current study, which is substantially longer than in most of the previous studies, our results can not directly be extrapolated to an eight hours working day. Working days up to eight hours with frequent rest breaks are quite normal in an occupational setting.

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Chapter 5

The effect of work pace on workload, motor variability and fatigue

"The effect of work pace on workload, motor variability and fatigue during simulated light assembly work", Tim Bosch, Svend Erik Mathiassen, Bart Visser, Michiel de Looze & Jaap van Dieën
Ergonomics (2011), 54 (2), 154-168

Abstract

This study investigated the effect of work pace on workload, motor variability and fatigue during light assembly work. Upper extremity kinematics and electromyography (EMG) were obtained on a cycle-to-cycle basis for eight participants during two conditions, corresponding to "normal" and "high" work pace according to a predetermined time system for engineering. Indicators of fatigue, pain sensitivity and performance were recorded before, during and after the task. The level and variability of muscle activity did not differ according to work pace, and manifestations of muscle fatigue or changed pain sensitivity were not observed. In the high work pace, however, participants moved more efficiently, they showed more variability in wrist speed and acceleration, but they also made more errors. These results suggest that an increased work pace, within the range addressed here, will not have any substantial adverse effects on acute motor performance and fatigue in light, cyclic assembly work.

Statement of relevance

In the manufacturing industry, work pace is a key issue in production system design and hence of interest to ergonomists as well as engineers. In this laboratory study, increasing the work pace did not show adverse effects in terms of biomechanical exposures and muscle fatigue, but it did lead to more errors. For the industrial engineer, this observation suggests that an increase in work pace might diminish production quality, even without any noticeable fatigue being experienced by the operators.

Introduction

During recent decades a number of studies have identified generic occupational risk factors that are associated with musculoskeletal disorders in the arms, shoulders and neck. In the biomechanics domain, high external force demands, high movement velocities and accelerations of movements, repetitive movements and prolonged activity with little variation ("static loads") have been identified as generic risk factors at the individual level (Kilbom 1994, Bernard 1997, National Research Council and Institute of Medicine 2001). Furthermore, several studies have established that a number of factors inherent to the organization of work are associated with increased risks of developing musculoskeletal disorders in the upper extremity, probably by modifying the levels, frequencies and/or durations of exposure to the generic risk factors. These organizational determinants include overtime (Bergqvist et al. 1995), long working hours (Trinkoff et al. 2006) and a high work pace (Houtman et al. 1994).

In cyclic work, work pace is inherently linked to the frequency of repetitive movements (Andersen et al. 2003). However, while work pace is therefore claimed to be important to the risk of developing musculoskeletal disorders, it has received little attention in experimental research. Only a few studies have investigated the acute effects of work pace in an occupational setting (Odenrick et al. 1988, Arndt 1987) or in controlled experiments (Mathiassen and Winkel 1996, Sundelin 1993, Laursen et al. 1998, Visser et al. 2004, Selen et al. 2006). In general, these studies showed that a higher work pace was associated with higher levels of shoulder muscle activity, signs of muscle fatigue, and an increase in perceived discomfort.

Since work pace relates directly to productivity, it is also of prominent importance in an engineering context (Wells et al. 2007). This applies to any kind of production system, but is particularly evident in flow-type production, such as an assembly line in the manufacturing industry. In this case, the line is typically designed to operate at a certain cycle time, controlled by machines or by the operators. Optimal system performance not only requires the target pace to be reached at each work station on average, but it also relies on operators showing minimal temporal variability in work pace. Cycle time variability between and within individuals inevitably leads to time losses, in particular for lines without buffers between stations (Wild 1994). Engineers in the manufacturing industry often use predetermined time systems (e.g. Methods-Time Measurement, Ready Work Factor) when determining a target work pace, but these standards do not account for the effects of between- and within-subject variability on time losses in the production system. The between- and within-subject variability in assembly work pace is, however, considerable (de Looze et al. 2005, Dempsey and McGorry 2004, Möller et al. 2004), and so the strive for a stable cycle time presents a genuine challenge to engineers.

In addition to this temporal variability, all cyclical activities show kinetic and kinematic variability between cycles. This “motor noise” is an inherent property in sensorimotor control, and so it appears in very stereotyped tasks such as gait (e.g. Terrier and Schutz 2003) , as well as in occupational tasks of differing complexity (e.g. Hammarskjöld et al. 1989, van Dieën et al. 2001, Mathiassen et al. 2003, Jackson et al. 2009, Madeleine et al. 2008b). Motor variability is of interest to the engineer to the extent that it may interfere negatively with performance in terms of quality and error rate, even if not all kinematic and kinetic variability will have adverse effects on target performance (Domkin et al. 2005). From an ergonomic viewpoint, on the other hand, motor variability has been suggested to be generally beneficial to the physiological and medical outcome of physical work, in being an intrinsic source of exposure variation (Mathiassen 2006) allowing tissues to temporally recover from preceding exposures (Bongers et al. 2002, Järvi and Uusitalo 2004).

In the shoulder region, variability appears possible, and present, at the level of individual motor units (Thorn et al. 2002), between parts of the same muscle (Mathiassen and Winkel 1990, Jensen and Westgaard 1997) and among different muscles with similar biomechanical functions (Palmerud et al. 1995). Laboratory studies have suggested that individuals differ in the size of this motor variability, and that a larger variability is associated with attenuated development of fatigue (van Dieën et al. 1993, Mathiassen and Aminoff 1997, Farina et al. 2008). Motor control research even suggests that variability can be trainable (Wilson et al. 2008). In low-level, long-lasting tasks, exposure variation may therefore be increased, with expectedly beneficial effects, by promoting an individual’s ability to perform his work using different motor solutions, in addition to implementing organizational measures such as job rotation or increased break allowances (Mathiassen 2006, Straker 2003, Wells et al. 2007). Determinants of motor variability have lately received increased attention in occupational research (e.g. Madeleine et al. 2008a, Madeleine et al. 2008b, Madeleine and Madsen 2009) as well as in sports science (Bartlett et al. 2007).

Since, as mentioned above, work pace influences biomechanical exposure levels (Mathiassen and Winkel 1996, Odenrick et al. 1988, Sundelin 1993, Laursen et al. 1998), it may well be a determinant of motor variability, but this has to our knowledge not been investigated in an occupational context.

In the present study, we investigated the effect of work pace on motor patterns in a light, simulated assembly task by assessing the level and cycle-to-cycle variability of a number of parameters describing upper extremity kinematics and muscle activity. The effect of work pace on physiological responses was also addressed through recordings of maximum force generating capacity, EMG manifestations of muscle fatigue, pressure pain threshold, and perceived fatigue.

Methods

Participants

Eight right-handed, healthy, females (mean age 20.5 (SD 1.8) years, weight 61.1 (SD 12.1) kg, height 1.69 (SD 0.05) m, BMI 21.3 (SD 3.6) kg/m^2) volunteered to participate in the study. Exclusion criteria were disorders or pain in the neck and shoulder region. Participants were asked to avoid heavy exercise of the arms during the week preceding the study. All participants gave their written informed consent prior to the start of the study. The study was approved by the local Ethics Committee.

Procedure

The participants performed a two-hour pick and place task at two work paces (see below) on two different days with one or two days in between. The order of the two work paces was, to the extent possible, randomly assigned to a particular participant, while securing a balanced design of task order between participants. To ensure familiarity with the task and to offset a learning effect across trials, a training session was performed one day before the first work pace experiment. Training was carried out at the high work pace (described below), and lasted until a stable work rhythm was achieved, one hour as a minimum. All sessions were performed in a laboratory at a constant ambient temperature of 22°C. The task was performed with both hands, but given that the dominant arm is more fatigue-resistant than the non-dominant arm (Farina et al. 2003), EMG, kinematics and pressure pain threshold were only measured for the non-dominant side.

Task

The task involved repetitive pick and place actions, so as to simulate industrial assembly. The task was performed using a Perdue pegboard (Purdue Pegboard Model 32020, Lafayette Instrument Company, Lafayette IN) centrally positioned in front of the participant. Participants had to pick, place and remove 3 pins, 3 collars and 3 washers in a fixed order with the left and right hand simultaneously. Bins with these components were placed to the left and the right of the participant (Figure 5-1). At the start and end of each cycle, participants had to move the pegboard to a fixed position and push a button in front of them. Participants were free to choose their own working technique and were only instructed on the sequence of actions. First, sitting height was individually adjusted to obtain a knee angle of 90 degrees. After that, working height was standardized by placing the table surface 5 cm below the position of the wrist when the elbow was 90° flexed and the participant sat in an upright position. Table and chair height were noted at the first experiment and re-used in the second. An auditory signal was given by a clock at the intended completion of each cycle and participants were asked to keep to the cycle time as closely as possible.

Work pace was calculated using the Ready Work Factor (RWF) analysis, a predetermined time system for predicting standard times in new or existing jobs (Niebel and Freivalds 2003). On the basis of the RWF analysis, a “low” work pace (LWP) condition was selected, which the participants were expected to be able to perform efficiently and without errors after a short training session. The LWP was set at a cycle time of 48 s and could be seen as a “normal” work pace according to industrial time standards. A “high” work pace (HWP) condition was selected so as to represent a difficult and stressful task for the participants. The HWP cycle time was set at 38 s, i.e. equivalent to 126% of the pace in the LWP condition, and it represents a realistic work pace in the manufacturing industry.

***Figure 5-1**. Workstation setup from a side (left) and back view (right). A more detailed description is given in the task paragraph.*

Kinematics

Three-dimensional postures and movements were recorded using Optotrak (Northern Digital Inc., Canada, sampling rate 200 samples/s). Markers were placed on the left arm and shoulder at the styloid process of the ulna, the epicondylus of the humerus and at the acromion. Reference markers were placed on one of the bins and at the button in front of the participant. The marker positions were marked with a waterproof pencil, in order to place the markers at exactly the same position in both conditions. The data were low-pass filtered with a Butterworth filter (2^{nd} order, cut-off frequency 10 Hz).

Short periods (less than 0.5 seconds) with missing values for shoulder, elbow or wrist data were replaced by spline interpolation or estimates on the basis of available data. On the basis of the wrist kinematics measurements, the dynamic movements when lifting and transferring the pegboard at the start and end of each cycle were identified and used to eliminate these parts of the cycle from further analysis. Thus, further analysis focused on the assembly part of the cycle, i.e. pick and place of small components.

This part lasted 40.9 s and 32.3 s in the LWP and HWP conditions, respectively, according to the RWF analyses. For each assembly cycle, the following measures were obtained using custom scripts in MATLAB (The MathWorks, Inc.):

- Distance covered, i.e. the distances travelled by the wrist, elbow and shoulder relative to the button in front of the participant. Because of missing values due to markers that were obscured from the sight of the camera, the average movement speed over each cycle within the available episodes of data was calculated. Subsequently, the weighted mean speed over all episodes was determined and the distance covered was calculated by multiplying the weighted mean speed with the exact cycle duration.
- Average speed, i.e. the mean value across the assembly cycle of the derivatives of the wrist, elbow and shoulder distance.
- The root mean square of the total acceleration time series of the wrist, elbow and shoulder; acceleration being obtained as the second derivative of distance.
- The average 3D shoulder position relative to the button in front of the participant.

The distance covered by the wrist relative to the shoulder was calculated to obtain a measure of total arm movement. The position of the wrist relative to the shoulder position was therefore used. The distance covered by the wrist relative to the elbow was calculated to evaluate the contribution of the forearm to the distance covered by the wrist. The contribution of the upper arm to the wrist distance was expressed through the position of the elbow relative to the shoulder.

Surface EMG

Deltoid and forearm extensor EMG was measured by a porti 16/ASD system (TMS, Enschede, The Netherlands). Bipolar Ag/AgCl (Medicotest, Ambu A/S, Baltorpbakken 13, DK-2750 Ballerup) surface electrodes were positioned according to Hermens et al. (2000), however using an interelectrode distance (IED) of 25 mm. A reference electrode was placed on the C7 spinous process. Before the electrodes were applied, the skin was shaved, scrubbed and cleaned with alcohol. EMG signals were band-pass filtered (10-400 Hz) and continuously sampled during the entire work bout at a sampling rate of 1000 samples/s.

EMG from the left trapezius, pars descendens, was recorded using a linear adhesive array of eight electrodes (bar electrodes, 5 mm x 1 mm size, 5 mm IED, LISiN-SPES Medica, Italy). Prior to electrode placement, the descending part of the trapezius was assessed during preliminary test contractions with a dry array of eight electrodes (silver bars, 8 electrodes, 10 mm IED) as previously described by Farina et al. (2002). The main muscle innervation zone location was identified for the trapezius muscle from the surface EMG recordings. The skin was gently abraded and cleaned with water. The adhesive array was positioned between the detected innervation zone location and the distal tendon region of the muscle aligned along a straight line between the acromion and the C7 spinous process (Jensen et al. 1993b). A reference electrode was placed at the right sternum. All EMG electrode positions were marked with a waterproof pencil, in order to exactly reproduce the electrode placement in both work pace conditions. Upper trapezius EMG was amplified 5000 times (64-channel surface EMG amplifier, SEA64, LISiN-OT Bioelectronica, Torino, Italy; 3-dB bandwidth, 10–500 Hz), sampled at 2048 samples/s and A/D converted in 12 bits (National Instrument® acquisition board, Austin, USA).

For each work cycle, the mean EMG amplitude of the deltoid and forearm extensors was determined by averaging the bandpass filtered (10–400 Hz) and rectified signal, obtained by taking the absolute value of the each sample. The mean power frequency (MPF) was calculated using Welch’s method (Welch 1967). For the linear electrode array on trapezius, the average values of the amplitude and MPF over the mid 4-5 channels were calculated. The outer channels were excluded from analysis due to low signal to noise ratios for almost all trials. For all muscles, EMG amplitudes were normalized using a Maximum Voluntary Excitation (MVE) procedure (Mathiassen et al. 1995). Maximal EMG amplitudes were obtained from two 5-s maximum voluntary contractions (MVC) performed against manual resistance at the start of each experimental day. Each MVC was followed by a rest period of at least 1 min. A 1-s moving window was used to determine the maximum rectified and averaged value for each muscle across both MVC.

Maximum Voluntary Force (MVF)

The MVF was determined while the participant was seated on a chair with the knees flexed 90°. Adjustable straps were positioned over the middle of the upper arms, with the participant maintaining a maximally upright position of the upper body. The participants were asked to perform maximal abduction of both arms against the resistance provided by the straps for four seconds. To obtain MVF, a strain-gauge force transducer (Futek, model FP11463-00533-B, Irvine, USA) was connected to the left strap. Force data were sampled with 1000 samples/s and averaged over the sample period. The maximal force over three trials was considered to be the MVF. Each trial was followed by a short rest period. The MVF was measured directly before and after the experimental task.

Performance

The total cycle time was determined from the button trigger signal. The actual cycle time of the assembly part was derived from the kinematic data as described above. Furthermore, work quality was measured by the average number of errors per 10-minute period, as observed by the experimenter. An error was defined as an action not accounted for in the RWF analysis (e.g. dropping a component).

Perceived Fatigue

Perceived muscle fatigue in the neck and shoulder area was rated every 15 minutes during the trial using the CR-10 Borg scale (Borg 1982, Åhsberg and Gamberale 1998, Strimpakos et al. 2005). The participant was acquainted with the Borg scale during the training session.

Pressure Pain Threshold (PPT)

PPT in the upper trapezius and deltoid muscle regions was measured before and after each trial by use of an algometer (Activator Methods, FPK 20, 20Lb x 25Lb, Phoenix, USA) as previously described (Mathiassen and Winkel 1996). Recordings of PPT in the shoulder region have been used extensively to evaluate changes in soreness in experimental (e.g. Nakata et al. 1993, Mathiassen and Winkel 1996, Hidalgo-Lozano et al. 2010) as well as clinical studies (e.g. Mathiassen et al. 1993, Nielsen et al. 2010), based on the notion that a changed PPT is a relevant indicator of altered pain perception (Fischer 1987). The participant was asked to give a signal when the perception changed from ‘pressure’ to ‘pain’. The corresponding pressure value (Pa) was noted as the participant’s PPT. Two determinations of threshold were made and their average was used as the participant’s PPT.

Cycle-to-cycle variability

Cycle-to-cycle variability was expressed in terms of the median absolute deviation (MAD), as described by Shevlyakov and Vilchevski (2002). As indicated by its name, this estimator is the median of the absolute differences between individual sample values and their common median. This estimator of variability is more robust to outliers than the standard deviation or the coefficient of variation (Chau et al. 2005). Cycle-to-cycle variability was calculated for all EMG (Amplitude and MPF) and kinematic (distance covered, speed and acceleration of the wrist, shoulder position) parameters.

Statistical analysis

Differences between the high and low work pace conditions in mean cycle time, levels of EMG and kinematic variables were analyzed using Wilcoxon signed rank tests, i.e. using participants as their own controls. Differences in cycle-to-cycle variability for cycle time and EMG and kinematic variables, as expressed by the MAD, were also analyzed using Wilcoxon signed rank tests. Perceived fatigue (conditions), PPT, error (conditions) and maximum shoulder force data were analyzed using a Wilcoxon signed rank test. Error data were analyzed with Friedman’s ANOVA for repeated measures to assess the effects of the independent variable time (12 blocks of 10 min each) on the average number of errors and rating of perceived fatigue. Significance was accepted at $p<0.05$.

Results

The average assembly cycle time differed significantly – as intended – between the LWP and HWP conditions (p=0.012, Z=2.5), and both were very close to the pre-determined time standard set by the RWF system, i.e. 40.7 s and 32.4 s, respectively. Cycle time variability did not differ significantly between paces (MAD= 1.19 and 1.27 for the LWP and HWP; p=0.48, Z=0.7).

Ideally the protocol would result in 190 and 150 complete cycles for each participant in the HWP and LWP condition, respectively. However, due to insufficient quality of the recordings of deltoid and forearm EMG, and of kinematic data, on average 178 and 140 cycles per participant were accepted for further analysis in the two conditions. Missing values were mainly due to poor visibility of the reflective markers. For the multi-array trapezius EMG, insufficient recording quality led to only 156 and 122 cycles, on average, being included for the HWP and LWP conditions, respectively.

Workload

The average EMG activity levels for the upper trapezius muscle were 12.4 %MVE (HWP) and 9.2 %MVE (LWP) as shown in figure 5-2. The deltoid muscle showed an average activity of 5.1 %MVE and 5.5 %MVE and the forearm extensor muscle activity was 6.2 %MVE and 5.0 %MVE (Figure 5-2) in the HWP and LWP condition, respectively. None of the differences between conditions were statistically significant.

Analysis of the kinematic data showed that the wrist was moved more efficiently during the HWP condition, as indicated by a 6% shorter distance covered (Table 5-1; p=0.012, Z=2.5). As expected, the average speed and acceleration of the wrist were higher during the HWP condition (Figure 5-3a; p=0.012, Z=2.5 and p=0.017, Z=2.4, respectively).

The distance covered by the elbow relative to the wrist was calculated as a measure of the contribution of the forearm to wrist movement (Table 5-1). This distance was significantly shorter at the HWP (p=0.012, Z=2.5). The contribution of the upper arm to wrist movement was expressed as the movement of the elbow relative to the shoulder, and again the distance was shorter for the HWP (Table 5-1; p=0.017, Z=2.4). However, the relative contributions of upper and forearm movement to the distance travelled by the wrist did not change with work pace. The pattern of arm movement was therefore independent of work pace.

No significant difference between the HWP and LWP was found for the distance covered by the shoulder during a work cycle (p= 0.78, Z=0.3). The shoulder was, however, placed in a significantly more forward (p=0.017, Z=2.4) and lower (p=0.036, Z=2.1) position during HWP than during LWP (Figure 5-4a). However, times series of shoulder positions differed substantially between participants (for an example see Figure 5-5). It appeared that some participants showed clear temporal changes while others had a stable shoulder position. No systematic differences were found between the HWP and LWP in this respect.

Table 5-1. *Average distance covered and variability in distance covered for the wrist, elbow and shoulder (upper part of the table), as well as the distance covered and their variability for these joints relative to each other (lower part of the table). Numbers refer to total distance covered per work cycle.*

	Average				**Variability (MAD)**			
Distance covered	**High**		**Low**		**High**		**Low**	
Wrist (m)	**9.3**	(0.4)	**9.8**	(0.4)	0.29	(0.06)	0.26	(0.06)
Elbow (m)	**4.4**	(0.4)	**4.7**	(0.5)	0.22	(0.07)	0.20	(0.04)
Shoulder (m)	1.1	(0.1)	1.1	(0.2)	0.10	(0.04)	0.09	(0.03)
Elbow - Shoulder (m)	**4.1**	(0.4)	**4.4**	(0.5)	0.20	(0.06)	0.19	(0.03)
Wrist - Shoulder (m)	**9.2**	(0.5)	**9.6**	(0.4)	0.30	(0.10)	0.26	(0.06)
Wrist - Elbow (m)	**9.2**	(0.4)	**9.7**	(0.4)	0.28	(0.06)	0.26	(0.06)

Numbers in brackets indicate standard deviations.
Significant differences (p<0.05) between work paces ("high" vs. "low") are marked bold.

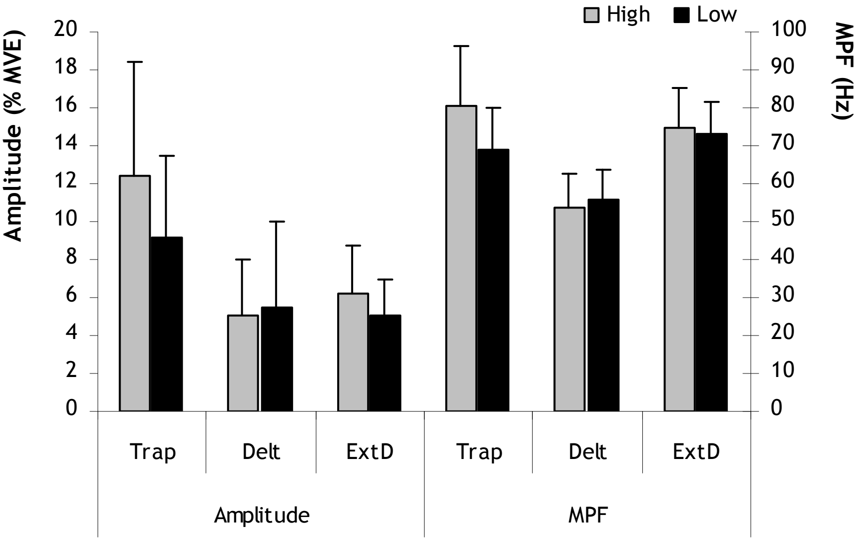

Figure 5-2. Average EMG amplitude and mean power frequency (MPF) for the upper trapezius (Trap), deltoid anterior (Delt) and extensor digitorum (ExtD) muscle in the high and low work pace (error bars indicate SD).

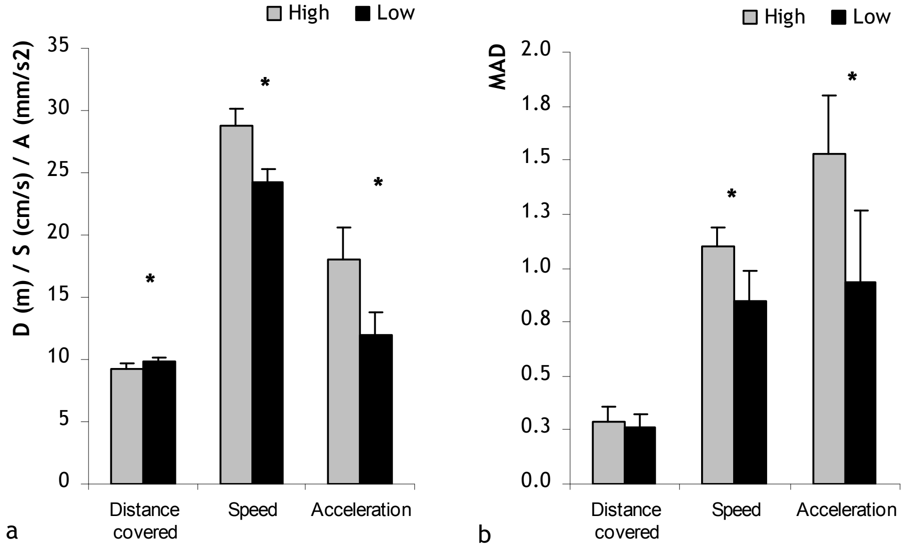

***Figure 5-3. a**. Average distance covered, speed and acceleration of the wrist for the high and low work pace. **b**. Average cycle-to-cycle variability (MAD) for distance covered, speed and acceleration of the wrist. Error bars indicate SD. * p<0.05*

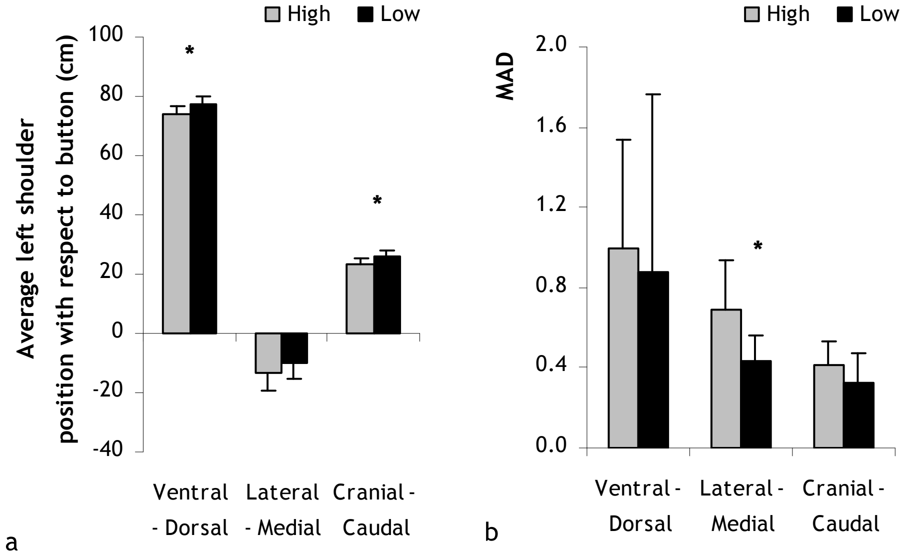

***Figure 5-4**. **a**. Average left shoulder position for both conditions in three dimensions. Shoulder position is expressed as the distance of the shoulder with respect to the push button in front of the participant. **b**. Average cycle-to-cycle variability (MAD) for shoulder position in three dimensions. Error bars indicate SD. * $p<0.05$*

Variability

An evident cycle-to-cycle variability was found for all investigated kinetic and kinematic parameters in both the HWP and LWP conditions (Figure 5-3b, Figure 5-4b and Figure 5-6).

The upper trapezius and deltoid EMG amplitude (Figure 5-6) did not show significant differences in cycle-to-cycle variability (p=0.58, Z=0.6 and p=0.40, Z=0.8) between HWP and LWP. However, the extensor digitorum (Figure 5-6) showed a significantly larger variability in EMG activity across work cycles in the HWP condition compared to the LWP (p=0.012, Z=2.5).

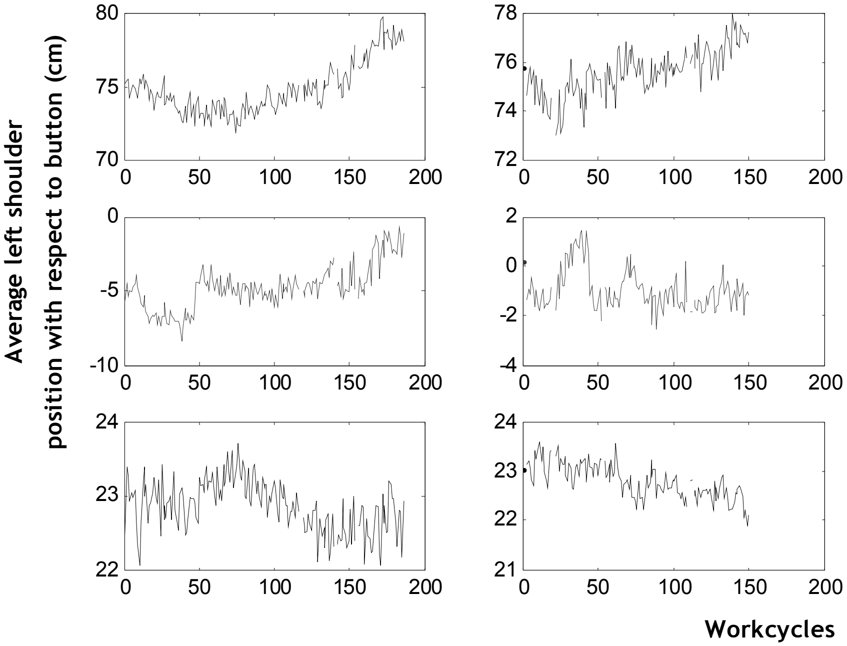

***Figure 5-5**. Temporal changes in shoulder posture over time for one participant. The left panels represent the HWP condition, the right panels represent the LWP condition for ventral-dorsal (upper), lateral-medial (middle) and cranial-caudal (lower) movements. This participant showed examples of both smooth temporal shifts (upper left) and abrupt shifts in shoulder position (middle left).*

As expected from the higher average speed and acceleration of the wrist during the HWP, the cycle-to-cycle variability in wrist speed and acceleration was also larger (Figure 5-3b; p=0.017, Z=2.5 and p=0.049, Z=1.9 respectively). The variability, in distance covered by the wrist, between cycles was not significantly different between conditions (Figure 5-3b; p=0.16, Z=1.4).

The HWP condition was associated with significantly more variability in the sideward position of the shoulder (Figure 5-4b; p=0.017, Z=2.4) than the LWP condition, and a tendency towards significantly more variability in the upward position (Figure 5-4b; p=0.067, Z=1.68). When the amount of variability in all directions was summarized, six out of eight participants showed more variability in shoulder posture during the HWP condition, but the difference was not statistically significant (p=0.16, Z=1.4).

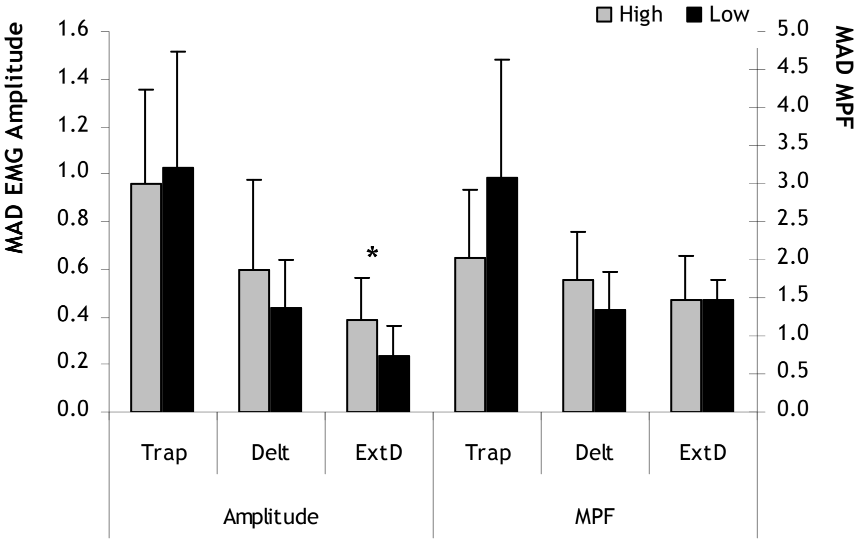

***Figure 5-6**. Average cycle-to-cycle variability (MAD) for the EMG amplitude and mean power frequency (MPF) of the upper trapezius (Trap), deltoid anterior (Delt) and extensor digitorum (ExtD) muscle in the high and low pace (error bars indicate SD). * $p<0.05$*

Manifestations of fatigue and pain perception

Perceived fatigue increased significantly across time from a Borg scale ranking of 0.3 to about 3.5 in both work paces (Figure 5-7; $p<0.001$, x2=58.1), but the level of fatigue and its rate of increase did not differ significantly between the LWP and HWP ($p=0.307$, $Z=1.4$).

The absolute maximum shoulder abduction force varied widely between participants before the start of both conditions (227-402N and 214-340N for the HWP and LWP, respectively). While maximum force had decreased after the work bout for seven participants at both work paces, this change was not statistically significant ($p=0.12$, $Z=1.5$). Work pace did not have a significant effect on the decrease in maximum shoulder force ($p=0.86$, $Z=0.2$).

In the HWP condition, PPT in the trapezius region decreased to 294 kPa from a pre-exercise mean value of 333 kPa. The corresponding PPT in the deltoid region decreased to 196 kPa from 235 kPa at baseline. In the LWP condition PPT decreased to 255 and 206 kPa, with baselines at 284 and 235 kPa, for the trapezius and deltoid regions, respectively. The PPT for the upper trapezius region showed a tendency towards a decrease over time (p=0.06, Z=1.8) whereas the deltoid region PPT significantly decreased over time (p=0.048, Z=2.0). No main effect of work pace was found for the two regions (p=0.9, Z=0.1 and p=1.0, Z=0.0, respectively).

No consistent evidence was found for a development of electromyographic manifestations of muscle fatigue, in terms of an amplitude increase concomitant with a shift of the frequency spectrum shifts towards lower frequencies (Basmajian and De Luca 1985). EMG amplitude and MPF did change over time in a number of participants, but in an inconsistent way.

Finally, participants made more errors per work cycle during the HWP (p= 0.017, Z=2.4) than during the LWP. On average, the number of errors per work cycle was almost double at the HWP (0.67 vs. 0.36). The number of errors did not change significantly (p=0.97, x2=4.1) across the two hour work period in any of the conditions.

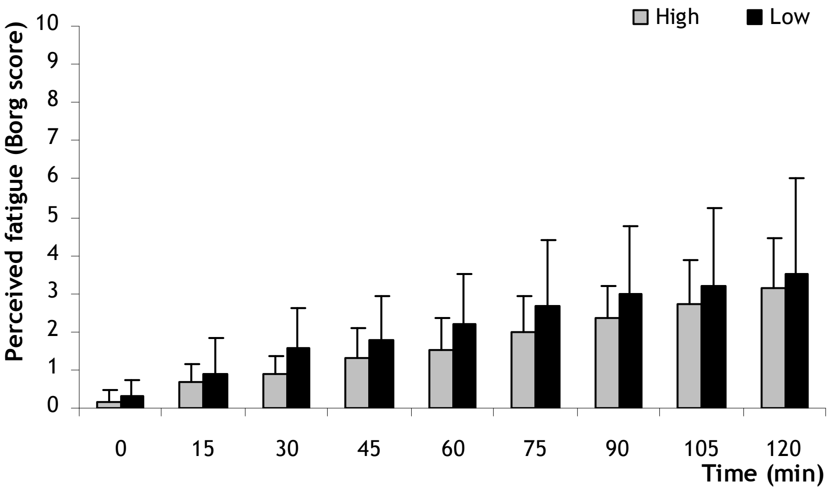

Figure 5-7*. Temporal changes in perceived fatigue in the neck and shoulder area for both work paces averaged across all participants. Error bars indicate SD.*

Discussion

The present exploratory study was designed to study effects of work pace in a simulated pick and place task on the level and variability of a number of kinetic and kinematic parameters, as well as on fatigue development. While muscle activity, perceived fatigue and pain sensitivity did not seem to be affected by work pace, participants moved more efficiently at the higher pace, yet with a larger variability. They also made more errors at the higher pace.

Representativeness of the study

The simulated assembly task performed by the participants was not an exact copy of an existing occupational assembly task. The task was based on the Perdue Pegboard task which has been used as one of several standardized tasks for assessing proficiency in assembly work (e.g. Tiffin and Asher 1948). The task included common elements of manual assembly work like picking, placing and positioning of components (e.g. Krawczyk and Armstrong 1991, de Looze et al. 2005). Work technique could, in principle, be decided by the participant, but the task instructions per se allowed for only small deviations from the prescribed work sequence. The average activity of the trapezius muscle corresponded to 10-15%MVC, which is similar to previous field studies on assembly work (e.g. Bosch et al. 2007, Christensen 1986). Whereas the basic task could be considered representative for occupational short cycle assembly work, several potential modifiers of motor behavior occurring in true occupational assembly were controlled in the current laboratory study, for instance occurrences of non-cyclic work tasks and scheduled or discretionary breaks. Both work paces were similar to industrial standards, corresponding to about 80% and 100% of the work pace expected from experienced workers in industry. The high work pace could be considered as a realistic industrial pace, whereas the low one can be seen as a pace typical for a learning phase.

The duration of the present 2-hours task is shorter than most work bouts in real life. Task duration could have an effect on several of the investigated variables, for instance due to accumulating fatigue. On the other hand, a recent review on muscle fatigue development during light manual work by de Looze et al. (2009) suggested that task duration did not differ between studies showing manifestations of fatigue and those not doing so. Thus, task duration may not be a critical concern with respect to representativeness.

The experiment was performed by inexperienced young female participants. Even though the simulated assembly work task was relatively easy, learning effects might have affected the motor performance of the participants. However, after analyzing the cycle-to-cycle variability in cycle times, we did not find a significant difference between the first and second measurement day. The training period provided prior to the actual measurements therefore seemed to be long enough to prevent substantial further learning effects. Notably, an increasing number of people work only for short periods (e.g. production peaks) at manufacturing companies (Brewster et al. 1997, Franco and Winquist 2002, Neumann et al. 2002), and would thus almost steadily be in a learning phase. Using inexperienced participants might therefore not hamper the translation of the results to practice.

The experiment was performed on eight participants, acting as their own controls. Due to the limited number of participants, results may not readily be generalized to a general population of young, healthy females, let alone participants of other ages, gender or disorder status. Also, some effects of changed work pace may have been left undetected due to insufficient statistical power. However, besides the EMG results (Figure 5-6), the numerical sizes of effects in the study that proved to be statistically insignificant do not lead to strong suspicions of type II errors.

Work pace and exposure levels

The current study suggested that the hand was moved more efficiently at a higher work pace level. A more detailed analysis showed that forearm and upper arm both contributed to this decrease in the movement distance of the wrist, whereas shoulder movement did not seem to contribute. The results did, indeed, show a more forward shoulder position, but the absence of an increased shoulder movement indicates that the upper body in general did not move more in the high pace condition. Maintaining a more inclined upper body posture, which will move the arms and hands closer to the pegboard, could explain the more economic movements in the high pace condition.

Also, the more economic movements in the high pace condition could be a sign of the participant “throwing” components to shorten movement time. A more detailed analysis of wrist movement did not, however, confirm this explanation; the start and stop positions of the wrist when getting and putting components was similar for both paces. Participants could also have chosen a more comfortable – while less efficient – strategy for putting and getting components in the low pace condition by approaching the bins more vertically. Analysis of the separate trajectories in each of the three orthogonal directions did, indeed, indicate that the total amount of movement in the vertical as well as both horizontal directions was smaller for the high work pace condition.

A higher work pace did not result in a higher muscle activity according to the EMG recordings. This stands in contrast to other experimental work pace studies quantifying workload by EMG (e.g. Laursen et al. 1998, Sundelin 1993).The diverging results might be due to differences between the studied tasks, including differing requirements for speed and acceleration. In our study, the increased work pace did not result in additional shoulder movement, and thus no additional requirements were put on the trapezius muscle for this reason (Kuijt-Evers et al. 2007). Also, the more forward, “engaged” upper body posture during the high work pace reduced the external gravitational torque on the moving arms, leading to a smaller force required from the muscles to support the arms. Finally, load sharing between the muscles in the upper extremity may differ between the work paces, including a transfer of activity in the high pace condition to synergistic muscles not recorded by our surface EMG electrodes (Palmerud et al. 1998).

The number of errors, measuring the quality of work, doubled when comparing the high to the low work pace condition. A study by Escorpizo and Moore (2007) showed the same trends: a decrease in cycle time resulted in substantially more errors. Also, our results are consistent with Fitts law (Fitts 1954) and an empirical study by Schmidt et al. (1979), stating that working at a higher speed will lead to lower accuracy on the target.

Work pace and motor variability

Previous studies on motor variability in occupational tasks have shown that several parameters describing motor patterns vary between cycles, even in simple short-cycle tasks such as lifting (Granata et al. 1999, van Dieën et al. 2001, Kjellberg et al. 1998) or industrial assembly work (Mathiassen et al. 2003, Möller et al. 2004). The current study confirmed these findings; a cycle-to-cycle variability, as measured by the MAD parameter, was seen in all kinematic variables. To the authors’ knowledge this parameter, which has statistical advantages over for example the standard deviation (Chau et al. 2005), has not been used before in short-cycle upper extremity work. A quantitative comparison with other studies investigating cycle-to-cycle variability of upper extremity kinematics (e.g. Madeleine et al. 2008b) was therefore not possible.

In the present study, an increase in work pace resulted in an increased cycle-to-cycle variability in movement speed and acceleration of the wrist. This finding is consistent with studies on signal-dependent noise (Harris and Wolpert 1998), showing an increase in kinematic variability with an increase in speed. Some recent studies suggest that motor variability can be modified by several additional factors relevant to occupational life. Acute and chronic pain altered the magnitude of motor variability in a simulated meat cutting task (Madeleine et al. 2008a). In that study, the authors showed that the development of pain within 6 months after employment was accompanied by less arm and trunk motor variability for a population of inexperienced butchers. Experience in itself had the opposite effect on motor variability; experienced participants showed more variability in trunk and arm kinematics compared to novices.

Since force fluctuations are larger as more motor units are recruited (e.g. Moritz et al 2005, Taylor et al. 2003), an association can be expected between the level of EMG activity and its variability. This was only partially supported in the current study. For the trapezius and deltoid muscles, the mean activity did not change with work pace, and neither did cycle-to-cycle variability. However, the forearm extensor (extensor digitorum) showed more cycle-to-cycle variability in EMG amplitude at a higher work pace, while the average amplitude did not differ between conditions.

Work pace and fatigue development

Since the high work pace resulted in shorter cycle times, larger accelerations and higher movement speed, fatigue could have been expected to develop at a faster rate than during the low pace. However, responses were similar in both conditions: perceived fatigue and PPT changed over time, but no signs of muscle fatigue were found according to standard EMG indicators, i.e. a decreasing MPF and increasing amplitude (Basmajian and De Luca 1985).

In our study, perceived fatigue levels even tended to be higher during the low pace than during the high pace, which was, at a first glance, surprising. However, in a study of a simulated short-cycle pick and place task, Escorpizo and Moore (2007) reported a similar result; discomfort did not increase as cycle time was halved. Also, a study by Krawczyk and Armstrong (1991) on a hand transfer task suggested that perceived fatigue did not have a straight-forward relation with work pace. A few other studies have investigated whether fatigue development during assembly work is related to work pace, yet with diverging results (Mathiassen and Winkel 1996, Sundelin 1993). Moreover, a general perceived fatigue may reflect fatigue dimensions that are not directly related to the physical load, such as sleepiness and lack of motivation (Åhsberg et al. 1997), and these factors may have differed to the disadvantage of the low pace.

The absence of clear signs of fatigue, even in the high-pace condition expected to cause at least some fatigue (de Looze et al. 2009), opens for a hypothesis that some of the kinematic effects of the work pace change may have had a *preventive* effect on cumulative fatigue development. An early study by Andersson et al. (1974) suggested that small postural changes in sitting might have an alleviating effect on fatigue. Recent studies confirm this notion by suggesting that discomfort during sitting is unconsciously prevented by abrupt changes in posture (Noro et al. 2005, Vergara and Page 2002). Further support is found in studies by Côté et al. (2005), Piggini et al. (2008) and Fuller et al. (2009). In the two latter studies, analysis of kinematic patterns during a pick and place, and a reaching task, respectively, revealed changes in upper extremity postures that were suggested to be triggered by fatigue development. In the study of repetitive hammering by Côté et al. (2005), fatigue-related changes were found in elbow kinematics and trunk motion, whereas cycle time and shoulder kinematics were not affected.

In the present experiment, abrupt shifts in posture were observed during both work paces, but discomfort ratings were too infrequent to establish whether these posture shifts had an immediate effect on discomfort. Participants that are not allowed to change technique, or that for some reason ignore a developing discomfort might be more at risk of developing muscle fatigue. It might be hypothesized that constrained kinematics obstructs temporal changes in regional muscle activity patterns that could counteract cumulative fatigue development, as indicated by recent EMG studies. Thus, Farina et al. (2008) showed that larger changes in the spatial distribution of EMG amplitude within the upper trapezius muscle was associated with less fatigue during an isometric contraction. In another study, Falla and Farina (2007) showed that such changes in the spatial distribution of EMG could be triggered by short increases in muscle loading, consistent with earlier studies indicating that short bursts of activity on top of an isometric contraction may stimulate motor unit substitution (Westad et al. 2003). A recent study of Van Dieën et al. (2009) showed that more variability in the EMG amplitude of the back extensor muscles resulted in less fatigue development, consistent with an earlier finding that participants with a better ability to alternate activity between parts of the lumbar extensor muscles had a better endurance in isometric back extension (Van Dieën et al. 1993). Some authors have even suggested that individuals able to effectively utilize intrinsic opportunities to obtain motor variability are less susceptible to musculoskeletal disorders

(Madeleine et al. 2008a, Mathiassen 2006, Mathiassen and Aminoff 1997, Kilbom 1994).

In the current study we focused our biomechanical analysis on the assembly part of the experimental task, but as a hypothesis, the somewhat heavier pegboard lifting action at the end of the work cycle might have had a preventive effect on fatigue development *per se*. In real-life assembly work, opportunities to vary muscle forces and postures will be even more extensive, which can explain that many studies have failed to demonstrate fatigue, even after hours of work at muscle activity levels that are, on average, compatible with those leading to substantial fatigue after few minutes of isometric activity (de Looze et al. 2009).

Conclusions

- In industrial engineering an increased work pace may be realized in order to increase human performance. Increasing the work pace might, however, lead to more production disturbances, even in the absence of fatigue among the workers, such as suggested by an increasing number of errors. In the present study, errors represented non-productive incidents like dropping components or putting components in the wrong bin. Errors were corrected by the participants and so did not have any effect on the final quality of the work. On the other hand these non-productive incidents might affect work rhythm and process flow, and in high risk environments they may have serious consequences.
- The present study showed some, if not a dramatic, cycle time variability within participants, but in less controlled assembly work this variability is probably larger. Work pace did not have an effect on the magnitude of cycle time variability, indicating that time losses in production caused by this variability will not be sensitive to the average work pace within the range studied.
- The results in the current study do not suggest directly negative physiologic effects on operators of an increased work pace. Changing the work pace within the limits investigated here seemed not to influence average workload, and it did not lead to pronounced fatigue Thus, work pace may have less impact on average workload than other organizational factors, such as work duration. While an increased work pace led to a larger motor variability, we do not suggest to use a higher work pace as an intervention to stimulate variation, since it will also increase the frequency of repeated actions. Other measures like job rotation have the intrinsic property to increase variation in workload without also increasing the repetitiveness of the task.

Acknowledgements

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Chapter 6

Fatigue and performance during prolonged repetitive work with breaks

"Fatigue, timing strategy and performance during prolonged repetitive work with interposed breaks", Tim Bosch, David Hallman, Svend Erik Mathiassen, Michiel de Looze, Eugene Lyskov, Bart Visser & Jaap van Dieën. Ergonomics - submitted

Abstract

This study investigated temporal changes in fatigue indicators, movement strategies and performance during short-cycle repetitive work with intermittent rest breaks. Eighteen participants performed six 7-minutes work bouts with repetitive arm movements at 0.5 Hz interrupted by 3-minutes breaks for a total duration of one hour. Electromyography (EMG) was collected continuously from the upper trapezius muscle, timing strategy and timing errors were obtained on a cycle-to-cycle basis, and perceived fatigue was rated before and after each bout. Clear signs of fatigue according to subjective ratings and EMG manifestations developed within each work bout. While the EMG frequency recovered during the breaks, EMG amplitude showed a gradual increase throughout the one hour work. Participants changed their temporal movement strategy gradually during the one hour work, but this was not sufficient to alleviate fatigue and maintain performance. The extent of fatigue development could not be predicted by initial levels of muscle activity, variability in muscle activity or timing strategy, and there were no significant correlations between EMG fatigue indicators and perceived fatigue.

Statement of relevance

Sustained performance of operators is essential to maintain competitiveness in the manufacturing industry. In this laboratory study of repetitive work with generous breaks, participants gradually changed their movement strategy, probably in order to counteract fatigue, but fatigue developed nevertheless and performance levels could not be maintained. Thus, in order to effectively counteract fatigue and sustain performance, industrial production should probably allow extensive spatial and temporal flexibility in the execution of short-cycle work.

Introduction

More than 60% of the European working population reports to perform repetitive hand or arm movements during more than 25% of their working time (Fourth European Working Conditions Survey 2007). Muscle fatigue, caused for instance by repetitive work, might be an important initiating factor in the development of neck and shoulder muscle disorders (e.g. Rempel et al. 1992, Takala 2002). Therefore, studies of fatigue development during repetitive work are justified as part of the efforts to develop guidance on how to prevent disorders. In sustained low-force activities, fatigue develops gradually, and a reduction in maximal force generating capacity is not necessarily obvious (Jones and Hunter 1983). Therefore, other physiological indicators are commonly used to assess fatigue. The electromyographic (EMG) signal from active muscles is commonly suggested to indicate fatigue when its frequency content decreases while, at the same time, the amplitude increases (Basmajian and De Luca 1985), even if this interpretation is not unchallenged (Hägg 1992, Cifrek et al. 2009). In continuous isometric contractions at large forces, EMG manifestations of muscle fatigue show a correlation with ratings of perceived fatigue (e.g. Öberg et al. 1994, Hummel et al. 2005, Troiano et al. 2008). However, during isometric contractions at low forces or with interposed rest pauses, conflicting results have been reported as to the presence of EMG signs of fatigue (e.g. Christensen 1986, Sundelin and Hagberg 1992, Szeto et al. 2005, Bosch et al. 2007, Öberg et al. 1994, Mathiassen 1993), and the relationship between objective and subjective indicators is less straight-forward. Thus, Sundelin and Hagberg (1992) and Szeto et al. (2005) reported a significant relationship between perceived discomfort and EMG manifestations of trapezius muscle fatigue, but no such relationship was established during repetitive pillar drilling (Christensen 1986), simulated assembly work (Mathiassen and Winkel 1996) or real-life assembly work (Bosch et al. 2007). In a recent study, de Looze et al. (2009) suggested that at low forces, the resulting perception of fatigue is influenced by psychological mediators in addition to those caused by muscle fatigue in itself. Also, at low-force, long-lasting efforts, the overall perception of fatigue, as captured by a Borg rating, may conceal different dimensions of fatigue, of which some cannot be expected to be correlated with EMG (Åhsberg et al. 1997).

Besides its perceptual dimension, fatigue could be expected to have a negative influence on task performance in many situations relevant to working life. Earlier studies, however, have shown inconsistent effects of fatigue on performance.

Tracking performance in terms of percentage time on target was not affected after a fatigue protocol (Selen et al. 2007), whereas Huysmans et al. (2008) showed a decrease in tracking performance during a similar task. Also studies of activities closer to real occupational tasks have shown conflicting effects of fatigue. Force output and movement frequency was significantly affected by fatigue in some studies of sawing tasks (Hammarskjöld and Harms-Ringdahl 1992, Côté et al. 2008), whereas other studies of similar activities did not find performance – movement time, trajectory, timing errors – to be decreased (Côté et al. 2002, Côté et al. 2005, Gates and Dingwell 2008). These conflicting results may be explained by differing responses depending on the outcome parameters used (Hoffman et al. 1992), fast recovery to normal capacity (Evans et al. 2003), and alterations in movement patterns so that performance can be maintained (e.g. Gates and Dingwell 2008, Côté et al. 2002). Movement patterns can be altered both in their spatial and temporal structure. Temporal structure or organization of work has been suggested to be influenced by several factors relevant to working life, including fatigue (e.g. Lomond and Côté 2010), acute and chronic pain (e.g. Madeleine et al. 2008a, Lomond and Côté 2010), work experience (e.g. Madeleine et al. 2008b), and the work pacing principle (e.g. Dempsey et al. 2010). However, to our knowledge, the development of such temporal movement adaptations during prolonged repetitive work has not been reported before. Furthermore, the relationship between fatigue and performance has not either, to our knowledge, been addressed in previous studies of prolonged repetitive work. Thus, ambiguity remains on the development of muscle fatigue during repeated, long-term contractions and its possible associations with perception and performance.

The development of fatigue is generally found to differ considerably between individuals performing a specific task. Some authors have suggested that individuals who are able to effectively utilize intrinsic opportunities to obtain motor variability can slow down or avoid fatigue development and that they may even be less susceptible to musculoskeletal disorders (Madeleine et al. 2008a, Mathiassen 2006, Mathiassen and Aminoff 1997, Kilbom 1994). As stated by Mathiassen (2006), variation in workload in spite of a maintained production can be achieved at different levels of the motor system: at a motor unit level within muscles, between subdivisions of a particular muscle, between muscles with overlapping biomechanical functions, and between muscle groups capable of delivering the same external output. It is reasonable to believe that individuals can differ in motor control at one or more of these levels.

More temporal variability in the EMG amplitude of back muscles (van Dieën et al. 2009) and more spatio-temporal variability of the EMG amplitude within the trapezius muscle (Farina et al. 2008) has been shown to be associated with slower development of electromyographic manifestations of fatigue. Van Dieën and co-authors (1993) showed that people with more alternating activity between different parts of the erector spinae muscle had longer endurance times in isometric back extensions; similarly Palmerud et al. (1998) suggested that load sharing between synergistic shoulder muscles might avoid or delay muscle fatigue development. Earlier findings have indicated that participants with a better ability to relax their muscles during a dynamic contraction sequence, expressed as a smaller ratio between EMG during the passive and active phases of a movement, show less fatigue after the task (Gerdle et al. 1989, van Dieën et al. 1996).

Recent studies have suggested that motor strategies may change due to, or in order to counteract, fatigue, even in terms of movement patterns. Kinematic changes have been shown in repetitive throwing (Forestier and Nougier 1998, Huffenus et al. 2006), hammering (Côté et al. 2005, Côté et al. 2008), sawing (Côté et al. 2002, Gates and Dingwell 2008) and reaching (Fuller et al. 2009, Lomond & Côté 2010). As an example, Côté et al. (2002) demonstrated that the movement amplitude of the elbow decreased in the course of repeated sawing, compensated by a more forward and lower shoulder position and an increase in movement amplitudes of shoulder, wrist and trunk. On the basis of more sophisticated analysis methods in a similar task, Gates and Dingwell (2008) also suggested that movement patterns were altered, yet without interfering with performance in terms of the intended production.

Most of the studies investigating kinematic patterns used another exercise protocol to provoke fatigue than that used for evaluating the effects of fatigue on motor patterns. As an example, Huffenus et al. (2006), Huysmans et al. (2008), and Côté et al. (2002) all used sustained isometric contractions at large relative forces to quickly induce considerable fatigue. A realistic temporal load pattern, including rest breaks, is usually not applied (e.g. Gates and Dingwell 2008), and gradual changes in movement patterns, timing and performance during such protocols are not well studied.

In the current study we investigated fatigue development, timing strategies and performance in short cycle repetitive work with intermittent rest breaks. The task was a simulation of industrial pick and place work at a production line, moving an object upward-forward and afterwards downward-backward, as described in Bosch et al. (2007).

The research questions in the current study were:

- Do manifestations of fatigue develop during a 1-hour short-cycle manual work task with intermittent breaks? Are EMG manifestations of muscle fatigue correlated with perceived fatigue?
- Does performance, timing strategy, variability in muscle activity and EMG amplitude ratio change during this task?
- Can the development of fatigue during the work bout be predicted by initial values of muscle activity level, variability in muscle activity, and timing strategy? Specifically:
    - Is high initial EMG amplitude associated with more fatigue manifestations? We hypothesized that participants with a higher initial EMG amplitude will show clearer signs of fatigue development.
    - Is a “small” EMG amplitude ratio at the start of the task predictive of less fatigue at the end of the task? We hypothesized that participants who are better able to decrease muscle load during the downward phase of the work cycle will be less fatigued after the whole work bout.
    - Is a large EMG amplitude variability at the start of the task predictive of less fatigue development during the course of the task? We hypothesized that participants who show more EMG variability (indicating less stereotyped movements) become less fatigued.
    - Does a timing strategy with proportionally more rest in the cycle, at the expense of faster movements, result in less fatigue development? We hypothesized that people who initially choose this strategy will experience less fatigue development.

Methods

Participants

Eighteen healthy, male participants (14 right-handed and four left-handed, mean age 24.2 (SD 4.3) years, weight 79.8 (SD 10.4) kg, height 183.5 (SD 3.4) cm, BMI 23.7 (SD 3.0) kg/m^2) volunteered to participate in the study. Exclusion criteria were disorders or pain in the neck, shoulders and arms. Furthermore, participants who had surgery or trauma in the neck, back or shoulders or fracture or dislocation in the neck or shoulders were excluded. Participants refrained from smoking and coffee intake thirty minutes before the experiment and were asked to avoid physical exercise during the two preceding days. All participants gave their written informed consent prior to the start of the study. The study was approved by the local Ethics Committee.

Procedure

The participants performed a 1-hour repetitive arm hand transfer task. The work cycles analyzed in this study were part of another study devoted to investigating effects of combining mental and physical loads (Mathiassen et al. 2008). In the main study, three different mental load conditions were introduced in breaks between bouts of the repetitive task, in experiments at least one week apart. Only data from the lightest mental load condition were used in the current study.

To ensure familiarity with the methods, the task and to offset a learning effect across trials, a training session was performed one day before the experiment. The training was continued until a stable work rhythm was achieved, or for a minimum of 3 minutes; i.e. about 90 work cycles. All sessions were performed in a laboratory at a constant ambient temperature of 22°C.

Work task

Six consecutive work blocks were performed, each consisting of 7 minutes of repetitive work and a 3-minutes rest break. During the rest break, participants performed a memory test in which they were presented letters on a computer screen in front of them, and asked at irregular intervals to recall the last presented letter.

The repetitive work task involved lifting and lowering of the arm and was performed with the dominant hand while the other arm was resting on the table in a predefined position. The repetitive work, illustrated in figure 6-1, consisted of moving a 300 g manipulandum held in the right hand (handle diameter 3 cm, outside dimensions: 0.09 x 0.06 x 0.12 m) between two targets at a frequency of 0.5 Hz (cycle time 2 s), as guided by a 1 Hz metronome signal. Participants were asked to hit the targets in synchrony with the metronome signals, while they were free to choose their own timing strategy and work technique within each half-cycle, between the metronome signals. The upper target was located at shoulder height and at a distance corresponding to an elbow angle of 160 degrees to avoid maximum stretching of the arm. The subject's sitting posture (knee angle at 90 degrees), distance between upper body and table (10 cm) and working height (table surface 1 cm under elbow height with relaxed shoulders) were standardized according to anthropometrics. A total of 210 work cycles were performed in each work block. Each of the targets was equipped with an electrical connector, which was activated whenever the manipulandum touched the target.

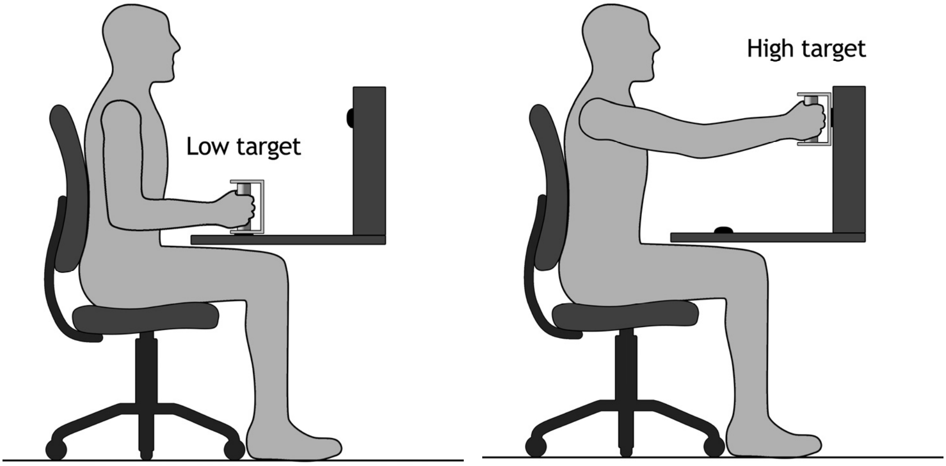


Figure 6-1. *The figure illustrates the workstation setup. Participants moved from the lower target (left) to the upper target (right) with a predetermined time allowance of 1 s and vice versa for the downward direction. The timing errors at both targets, expressed as the difference between the metronome beat and the actual hit at the target, as well as the waiting times at the high and low targets were recorded.*

Surface EMG

EMG from the right trapezius, pars descendens was measured by a BioPac MP150 System (BIOPAC Systems Inc, Santa Barbara, CA USA) and amplified with BioPac EMG100C modules (BIOPAC Systems Inc, Santa Barbara, CA USA). Pre-gelled bipolar Ag/AgCl surface electrodes (AMBU Neuroline 720, Baltorpbakken 13, DK-2750 Ballerup) were placed 2 cm lateral to the mid-point between C7 and the acromion according to Mathiassen et al. (1995), using an inter-electrode distance of 25 mm. A reference electrode was placed on the C7 spinous process. Before the electrodes were applied, the skin was shaved, scrubbed and cleaned with alcohol. EMG signals were continuously sampled during the entire work bout, band-pass filtered (10-500 Hz) and AD converted (16 bits at 2000 Hz). Data were analyzed using Spike2 software (Version 6, Cambridge Electronic Devices). For each half-cycle of work (1 s), the average EMG amplitude was determined by calculating the RMS values of the collected signal (Figure 6-2). The mean power frequency (MPF) of the signal was calculated using Welch’s method (Welch 1967). EMG amplitudes were normalized using a reference contraction procedure and expressed in percentage of the reference voluntary electric activity (%RVE; Mathiassen et al. 1995). A standard 15-s isometric reference contraction with the arms abducted at an angle of 90 degrees (Suurküla and Hägg 1987) was performed prior to the work bout while the participants sat at their chair. The position of the arms was visually controlled by the experimenter.

An EMG amplitude ratio was calculated a.m. Gerdle et al. (1989). The EMG amplitude during the downward movement was expressed as a percentage of the amplitude during the upward phase. With some cautiousness, this parameter might indicate the individual capacity to de-activate the muscle during the downward movement.

Perceived fatigue

Perceived muscle fatigue in the neck and shoulder area was rated before (PRE) and after (POST) every work block, using the Borg CR-10 scale (Borg 1982; Åhsberg and Gamberale 1998; Strimpakos et al. 2005). The participant was acquainted with the Borg scale during the training session. Perceived fatigue was also rated using the Swedish Occupational Fatigue Inventory (SOFI; Åhsberg et al. 1997). SOFI measures fatigue in five dimensions: lack of energy, physical exertion, physical discomfort, lack of motivation, and sleepiness. Participants answered the SOFI questionnaire before and after each work block, just after the Borg CR-10 rating.

Timing strategy and performance

The following parameters were derived for every work cycle on basis of the time stamps from the target connectors (Figure 6-2):

- Timing strategy, measured by the waiting time at the high (W1) and low target (W2) in seconds.
- Performance, expressed in terms of timing error. The timing error was defined as the time difference in seconds between the metronome beats and the actual first touch of the upper (E1) and lower (E2) target connectors. Positive timing errors indicated that participants were ahead of the metronome beat while negative indicated a late arrival to the target.

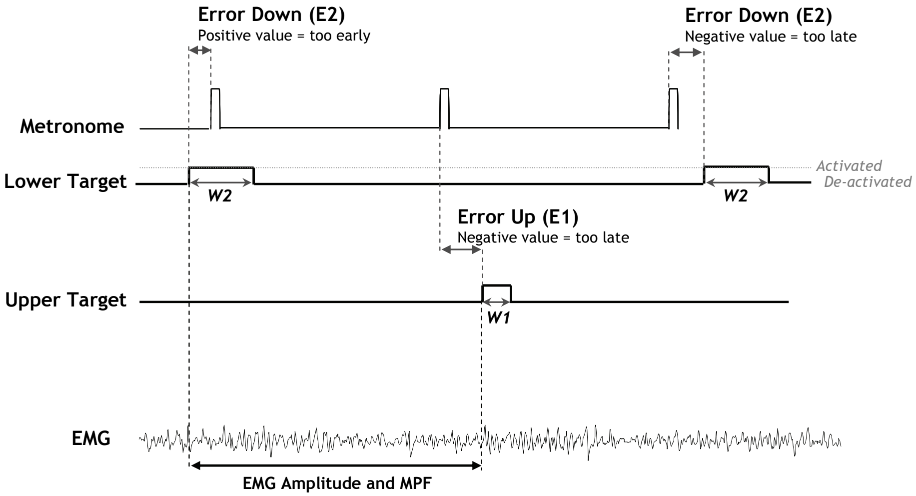


Figure 6-2*. Timing, performance and EMG parameters obtained for every work cycle. Waiting time at the high (W1) and low (W2) target was counted as long as the connector was activated. The timing error (performance) at the high target (E1) and low target (E2) was defined as the time difference between the metronome beat and the first touch of the target. EMG parameters were calculated as averages across each half-cycle.*

Data processing

Values of timing error, waiting time and EMG (amplitude and MPF) were investigated for each movement direction separately. Possible EMG manifestations of fatigue were addressed by comparing the average amplitude and MPF of the first 30 cycles of each work block (EARLY) with that of the last 30 cycles (LATE). In addition to average values, cycle-to-cycle variability across these cycles was assessed in terms of the median absolute deviation (MAD), as described by Shevlyakov and Vilchevski (2002) and Chau et al. (2005), and an EMG ratio was calculated EARLY and LATE in each block as the ratio between EMG amplitudes of the downward and upward movement.

Likewise, to analyze changes in timing strategy and performance, the average of timing errors and waiting times were calculated for the first 30 cycles of each work block (EARLY) and compared to the last 30 cycles of that work block (LATE).

To analyze recovery during the breaks the POST values of perceived fatigue after each work block were compared to the PRE values before the next work block. Likewise, the effects of recovery on EMG amplitude and MPF were assessed for each of the five recovery periods by comparing LATE-values with EARLY-values from the next block.

Statistics

Data inspection indicated that neither EMG, performance or timing data deviated from normal distributions. As the frequency distribution of perceived fatigue at a group level showed a large degree of skewness, a logarithmic transformation was performed on the ratings of perceived fatigue. Development of perceived fatigue over time – Borg CR-10 as well as SOFI ratings –was examined using a two-way ANOVA for repeated measures (ANOVA 1a) with independent variables work block (1-6) and time (pre/post). Recovery of perceived fatigue during the rest breaks was also analyzed using a two-way ANOVA for repeated measures (ANOVA 1b); independent variables rest break (1-5) and time (pre/post).

EMG amplitude and MPF changes over time were analyzed using a three-way ANOVA for repeated measures (ANOVA 2a) with independent variables direction (up/down), work block (1-6) and time-in-block (early/late). EMG recovery during the rest breaks was analyzed using a three-way ANOVA for repeated measures (ANOVA 2b); independent variables direction of movement (up/down), rest break (1-5) and time-in-block (early/late).

Effects on EMG amplitude variability were also examined with ANOVA 2a. EMG amplitude ratio was analyzed using a two-way ANOVA for repeated measures (ANOVA 3) with the independent variables work block (1-6) and time-in-block (early/late).

To examine changes in performance and timing strategy, a three-way ANOVA for repeated measures was applied (ANOVA 4) with the independent variables position (high/low target), work block (1-6) and time-in-block (early/late).

Degrees of freedom in the repeated measures ANOVAs were adjusted using Greenhouse–Geisser's epsilon to compensate for the effects of possible violations of the sphericity assumption (Twisk 2003). Interaction effects were post-hoc tested using a one-way ANOVA for repeated measures or Student's t-tests.

Associations between EMG variables, timing strategy and performance across participants were investigated using Pearson's product moment correlation coefficient (r), while relationships between variables describing perceived fatigue according to the Borg CR-10, timing strategy and performance were examined using Spearman's rho (r_s). Spearman's rho (r_s) was also used to describe the association between perceived fatigue according to the Borg CR-10 and SOFI-ratings of lack of motivation and sleepiness, and to determine association between perceived fatigue and EMG changes. Correlations between average waiting time and average timing error at the high and low targets were calculated using Pearson's product moment correlation coefficient. In all statistical analyses significance was accepted at $p<0.05$.

Results

Ideally the protocol would result in 210 work cycles per work block. However due to mechanical problems with the experimental setup, on average 207 (SD 2.5) work cycles were accepted per work block and used for further analysis.

Fatigue development

Perceived fatigue

Perceived fatigue according to the Borg CR-10 rating just before the first work block was rated 1.5 on average (Figure 6-3). None of the participants reported zero fatigue at this point. Perceived fatigue significantly increased during the 1-hour task as indicated by a main effect of work block ($F(3.9)=22.6$, $p<0.001$). A significant interaction ($F(3.1)=6.3$, $p=0.001$) between work block and time (pre-post measurements) was found. Post-hoc testing showed a significant increase of perceived fatigue within all work blocks ($F(3.1)=6.1$, $p=0.001$), the increase in perceived fatigue in the first block being significantly larger than in work block 2 and tending to be larger even compared to the other work blocks. The rest breaks resulted in a significant recovery of perceived fatigue according to the Borg CR-10 ($F(1)=79.3$, $p<0.001$).

According to the SOFI ratings, "physical discomfort", “physical exertion” and “lack of energy” increased across and within work bouts, while “sleepiness” only increased within work bouts (Table 6-1). The dimension "lack of motivation" did not show any significant change.

Borg CR-10 ratings did not show any relationship with lack of motivation ($r_s=-0.37$, $p=0.13$) or sleepiness ($r_s=-0.34$, $p=0.16$) as measured by SOFI. On the other hand a substantial correlation with the physical discomfort dimension in SOFI was found ($r_s=0.65$, $p=0.003$).

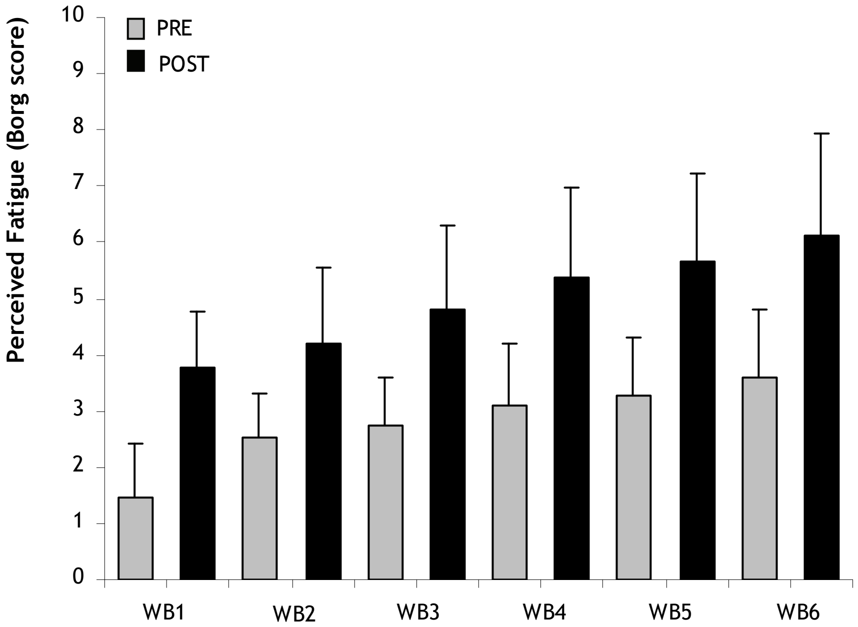


Figure 6-3*. Perceived fatigue before (grey) and after (black) each of the 6 work blocks (WB). Error bars represent the standard deviation between participants.*

EMG manifestations of muscle fatigue

The average EMG amplitude was 46.3 (SD 14.3) %RVE during the downward movement and 63.0 (SD 18.7) %RVE in the upward movement (Figure 6-4a). EMG amplitude differed with movement direction and work block in a significant interaction (Figure 6-4a and Table 6-2). Post-hoc examination showed that EMG amplitude increased across work blocks, for both the upward (F(2.3)=10.8, $p<0.001$) and downward movements (F(2.7)=7.2, $p=0.001$). Furthermore, a significant interaction effect between movement direction and time (early vs. late in block) was found. Post-hoc testing showed that in both directions the EMG amplitude increased within work blocks, but the mean increase (M_{diff}) was larger in the upward direction ($M_{diff\ up}=14.8$ %RVE, $SD_{up}=8.0$) than in the downward direction ($M_{diff\ down}=6.5$ %RVE, $SD_{down}=4.1$). The size of the amplitude increase was not significantly different between work blocks within each separate movement direction.

A significant decrease of the EMG amplitude as a result of the 3-minute breaks was found according to ANOVA 2b (F(1)=36.5, $p<0.001$), illustrating that recovery occurred in this sense.

As shown in table 6-2, a significant interaction between movement direction and time (early vs. late in work block) was found for the change in MPF illustrated in figure 6-4b. Post-hoc testing showed a significant decrease of the MPF within work blocks for both movement directions ($M_{diff\ up}$=-1.3 Hz, SD_{up}=1.9; $M_{diff\ down}$=-2.5 Hz, SD_{down}=2.5). However, no significant change of the MPF was found across all work blocks, suggesting that the overall MPF had not changed after one hour. Apparently, MPF recovered significantly during the 3-minute breaks between work blocks (ANOVA 2b; F(1)=15.5, p=0.001).

Relationship between perceived fatigue and EMG manifestations of muscle fatigue

For the six work blocks, Spearman's rho ranged between -0.06 and 0.33 for the correlation between changes in EMG amplitude and perceived fatigue (Borg CR-10), and between 0.03 and 0.26 for the correlation between MPF and perceived fatigue. None of these correlations were significant. In order to investigate whether changes in objective and subjective indicators of fatigue across the entire 1-hour work bout were correlated, differences between values at the very beginning of the first block and at the end the last work block were used. The resulting data showed a significant correlation (r_s = 0.58, p=0.012) between changes in EMG amplitude and perceived fatigue, while changes in MPF and perceived fatigue were not correlated (r_s= -0.13, p=0.62).

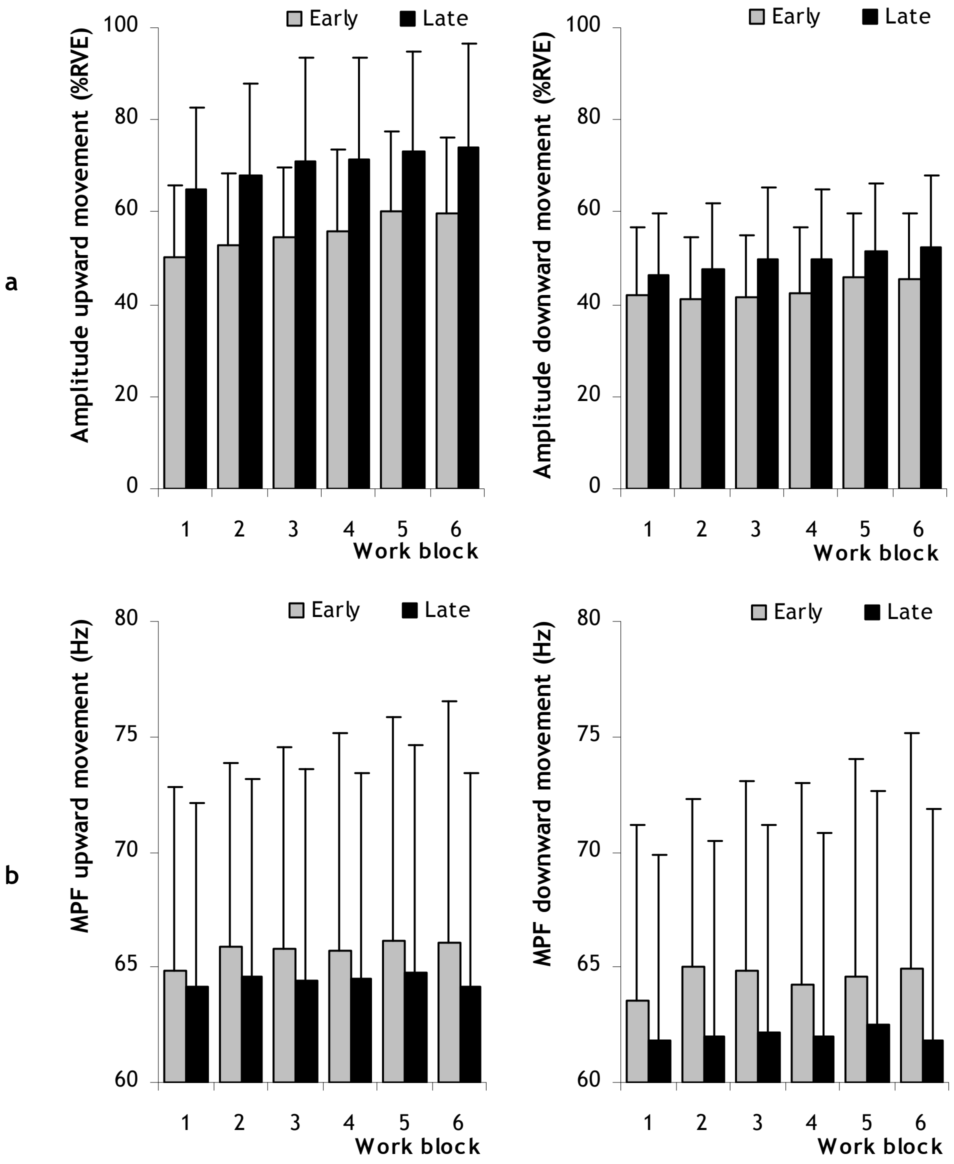


Figure 6-4. *EMG amplitude (**a**) and MPF (**b**) for the upward (left) and downward (right) movement at the beginning (Early) and end (Late) of each work block. As expected, the upward movement direction showed significantly higher average EMG amplitudes than the downward movement. Error bars represent the standard deviation between participants.*

Table 6-1. *Effects of Work block (6 blocks) and Time (pre/post) on perceived fatigue ratings (Borg CR-10 and SOFI) according to ANOVA 1a.*

ANOVA 1a	**Borg CR-10**			**Physical discomfort**			**Physical exertion**		
Factor	df	F	p	df	F	p	df	F	p
Work block 1-6)	1.7	22.6	**<0.001**	2.3	7.9	**0.001**	3.3	2.8	**0.043**
Time (pre/post)	1.0	121.6	**<0.001**	1.0	43.9	**<0.001**	1.0	34.0	**<0.001**
Work block * Time	3.1	6.3	**0.001**	3.6	2.3	0.073	2.8	2.2	0.10

ANOVA 1a	**Lack of energy**			**Sleepiness**			**Lack of motivation**		
Factor	df	F	p	df	F	p	df	F	p
Work block (1-6)	2.9	12.9	**<0.001**	2.5	1.3	0.288	2.4	2.5	0.081
Time (pre/post)	1.0	7.6	**0.014**	1.0	9.6	**0.006**	1.0	1.3	0.275
Work block * Time	2.7	8.9	**<0.001**	3.0	1.0	0.389	2.8	1.3	0.295

Degrees of freedom (df), F-values and p-values are shown for main effects and interactions. Significant results ($p < 0.05$) are boldfaced.

Table 6-2. *Effects of movement Direction (up/down), Work block (6 blocks) and Time-in-block (early/late) on average EMG amplitude (%RVE), MPF (Hz) and EMG amplitude variability according to ANOVA 2a.*

ANOVA 2a	**EMG amplitude**			**EMG MPF**			**EMG amplitude variability**		
Factor	df	F	p	df	F	p	df	F	p
Direction (up/down)	1.0	74.8	**<0.001**	1.0	43.6	**<0.001**	1.0	23.2	**<0.001**
Work block (1-6)	2.4	9.8	**<0.001**	1.4	1.1	0.340	3.0	5.9	**0.002**
Time in block (early/late)	1.0	64.8	**<0.001**	1.0	14.5	**0.001**	1.0	12.6	**0.002**
Direction * Work block	2.7	7.2	**<0.001**	3.4	0.4	0.745	3.2	2.3	0.088
Direction * Time in block	1.0	36.3	**<0.001**	1.0	12.5	**0.003**	1.0	4.4	0.051
Work block * Time in block	3.2	0.9	0.427	2.8	1.1	0.347	3.2	0.5	0.685
Direction * Work block * Time	3.1	1.6	0.197	3.8	0.8	0.532	3.1	1.0	0.387

Degrees of freedom (df), F-values and p-values are shown for main effects and interactions.
Significant results ($p < 0.05$) are boldfaced.

EMG variability and amplitude ratio

As shown in table 6-2 and illustrated in figure 6-5, EMG amplitude variability increased significantly during the 1-hour task. Furthermore, ANOVA 2a showed a significant interaction between work block and time-in-block. Post-hoc testing showed a significant increase in EMG variability within all work blocks with the largest increase in work block 1. The EMG amplitude ratio showed a significant interaction effect between work blocks and time-in-block (F(2.8)=4.9, p=0.006) according to ANOVA 3. Post-hoc testing showed a significant decrease over the course of the 1-hour task and a significant decrease within work blocks with the largest decrease in the first work block (Figure 6-6).

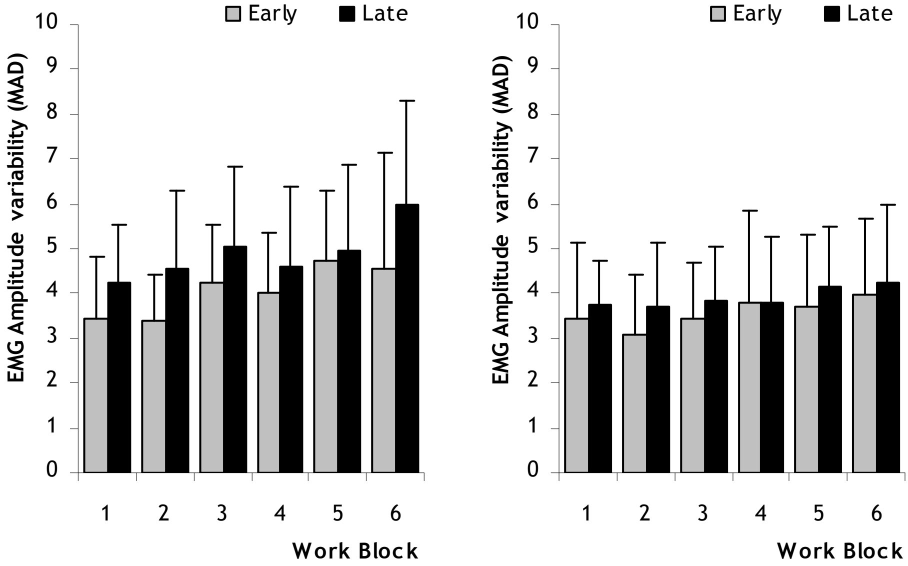


***Figure 6-5**. EMG amplitude variability (%RVE) for the upward (left) and downward (right) movement at the beginning (Early, grey bars) and end (Late, black bars) of each work block. Error bars indicate the standard deviation between participants.*

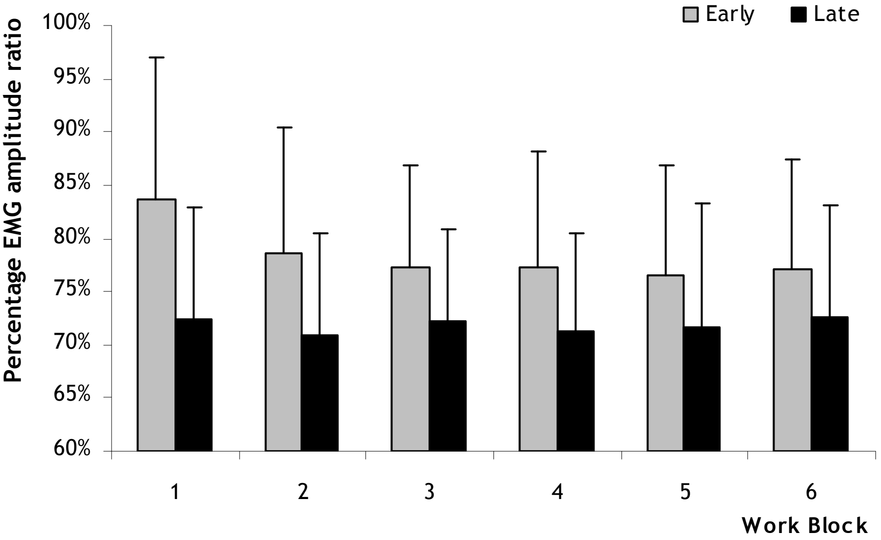


***Figure 6-6**. EMG amplitude ratio (ratio between the EMG amplitude during the upward and downward movement) at the beginning (grey) and end (black) of the six work blocks. Error bars indicate standard deviation between participants.*

Timing strategy and performance

As illustrated in figure 6-7, the average waiting time at the upper and lower target were 0.17 s (SD=0.06) and 0.24 s (SD=0.01), respectively. A main effect of position indicated that the average waiting time at the upper target was significantly shorter than at the lower target (Table 6-3). ANOVA 4 showed that the effects of position and work block interacted significantly. Post-hoc testing indicated a significant decrease of waiting time across work blocks at the upper target (F(3.8)=3.8, p=0.027) but no significant change for the lower target. Furthermore, a significant interaction effect between position and time-in-block was found. Post-hoc testing demonstrated a significant increase in waiting time within work blocks at the lower target (t(17)=2.2, p=0.045), whereas waiting time did not significantly change within work blocks at the upper target.

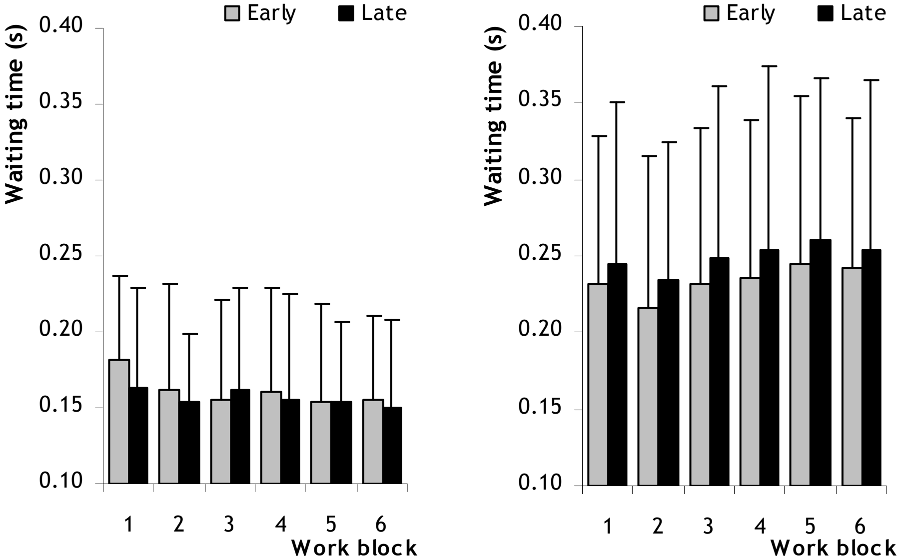


Figure 6-7. *The average waiting times (timing strategy) at the high (left) and low (right) targets at the start (grey) and end (black) of the each work block. Error bars indicate the standard deviation between participants.*

Table 6-3. *Effects of Position (high and low target), Work block (6 blocks) and Time-in-block (early/late) on average timing errors and waiting time according to ANOVA 4.*

ANOVA 4	**Timing strategy (average waiting time)**			**Performance (average timing error)**		
Factor	df	F	p	df	F	p
Position (high/low)	1.0	24.3	**<0.001**	1.0	21.9	**<0.001**
Work block (1-6)	2.7	1.2	0.335	3.8	11.6	**<0.001**
Time-in-block (early/late)	1.0	1.1	0.306	1.0	1.3	0.264
Position * Work block	2.8	5.2	**0.004**	3.0	1.5	0.228
Position * Time-in-block	1.0	12.0	**0.003**	1.0	13.8	**0.002**
Work block * Time-in-block	2.8	0.6	0.606	3.8	3.9	**0.008**
Position * Work block * Time-in-block	2.7	1.0	0.410	3.5	2.6	**0.050**

Degrees of freedom (df), F-values and p-values are shown for main effects and interactions. Significant results (p < 0.05) are boldfaced.

The average timing errors at the lower and upper target were 0.07s (SD 0.06) and 0.03s (SD 0.07), respectively. This main effect was significant (Table 6-3). A significant increase in timing errors over the course of all work bouts (Figure 6-8) appeared as a main effect of work block. A borderline significant three-way interaction effect between position, work block and time-in-block (F(3.5)=2.6, p=0.05) was found. Post-hoc testing indicated a significant decrease in timing errors at the upper target while changes in timing error within work blocks for the lower target were inconsistent. Average waiting time at the lower target was significantly correlated to timing error at the upper target (r= – 0.66, p=0.027) while no significant correlation between average waiting time and timing error was found for the downward movement (r= – 0.35, p=0.15).

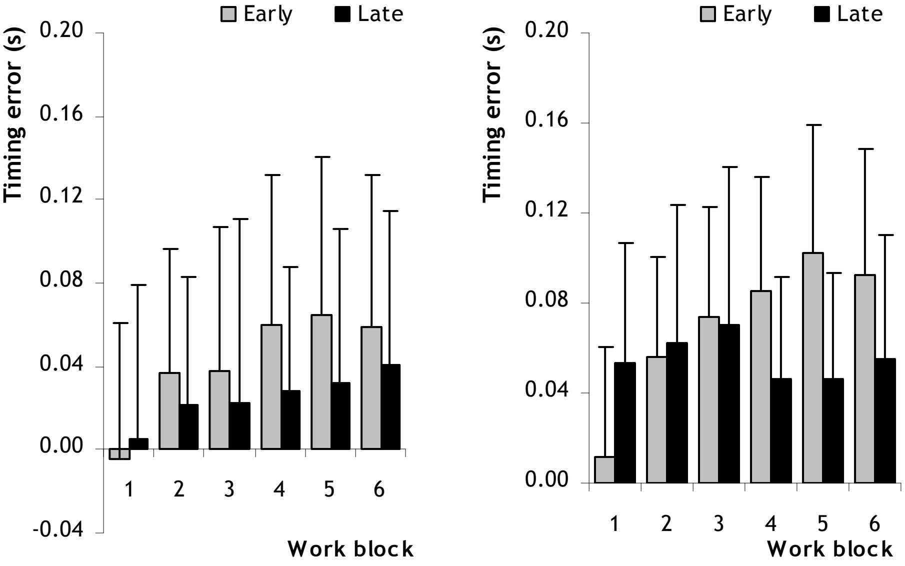


Figure 6-8. *The average timing errors (performance) at the high (left) and low (right) targets at the start (grey) and end (black) of the each work block. Error bars indicate the standard deviation between participants. Participants showed a significant decrease in timing error at the upper target within work blocks. This apparent improve of performance seems to be a consequence to the large extent of connecting to early at the start of each work block.*

Associations between manifestations of fatigue and performance

Fatigue manifestations were not significantly associated with decreased performance. No significant correlation was found between changes in perceived fatigue and changes in timing error (Upward movement r_s = – 0.14, p=0.59; Downward movement r_s = – 0.14, p=0.58). Furthermore, no significant correlations were found between EMG manifestations of fatigue and changes in performance.

Relationships between fatigue development and initial motor strategies

Initial timing strategy

The waiting time differed considerably between participants early in the first work bout (Upper target: range 0.13 - 0.37 s, Lower target: range 0.13 - 0.51 s). However, this initial timing strategy did not show any significant correlations with eventual changes in EMG (Table 6-4). Initial waiting time was not significantly correlated to changes in perceived fatigue either (Upward movement r_s = – 0.02, p=0.93; Downward movement
r_s = – 0.26, p=0.30). This suggests that individual strategies to avoid fatigue might not be present as a default.

Initial EMG levels

The inter-individual differences in initial EMG amplitude levels were considerable. Amplitude levels at the start of the first work bout ranged from 24-83 %RVE in the upward and 16-83 %RVE in the downward movement direction. However, no significant correlations were found between the initial EMG amplitude levels and EMG indicators of fatigue development (Table 6-4). Furthermore, no significant correlations were found between initial EMG amplitude levels and the change in perceived fatigue (r_s= – 0.01, p=0.97).

***Table 6-4**. Pearson correlation coefficients (r) and p-values for associations between, on the one hand, initial values of EMG amplitude, EMG amplitude variability, EMG amplitude ratio and waiting time and, on the other, EMG indicators of fatigue development.*

	Up		**Down**	
	r	p	r	p
EMG amplitude - EMG amplitude change	0.12	0.612	-0.25	0.309
EMG amplitude - MPF change	0.22	0.384	0.18	0.474
EMG amplitude variability –EMG amplitude change	0.21	0.390	-0.21	0.411
EMG amplitude variability –MPF change	0.25	0.316	.026	0.299
EMG amplitude ratio –EMG amplitude change	0.06	0.804	-0.08	0.765
EMG amplitude ratio –MPF change	0.41	0.089	0.24	0.342
Waiting time - EMG amplitude change	0.11	0.665	-0.14	0.591
Waiting time - MPF change	0.33	0.188	0.30	0.227

Initial EMG variability

A higher EMG amplitude variability at the beginning of the task, indicating more motor variability at a muscular level, was not significantly correlated to changes in EMG amplitude or MPF (Table 6-4). Furthermore, no significant correlation was found between initial EMG amplitude variability and changes in perceived fatigue (Upward movement r_s=0.42, p=0.82; Downward movement r_s=0.21, p=0.40).

Initial EMG amplitude ratio

No significant correlations were found between the initial EMG amplitude ratio and EMG indicators of fatigue development (Table 6-4). The amplitude ratio was not correlated with the change in perceived fatigue either (r_s = – 0.029, p=0.91).

Discussion

In the current study we investigated changes in temporal motor strategies and performance during series of highly repetitive arm movements with interposed rest periods, as well as the development of manifestations of fatigue. Furthermore, we explored whether the initial motor strategy predicted the eventual development of fatigue, temporal motor behavior and performance.

Manifestations of fatigue development

The mean EMG amplitude during the upward and downward movements (cf. Figure 6-4) was consistent with levels found in previous field studies of light manual handling tasks (Mathiassen et al. 2002), assuming that our sub-maximal normalization contraction required 15-20 percent of maximal capacity (Mathiassen and Aminoff 1997). We found clear signs of fatigue within each work bout, in terms of increased perceived fatigue, as well as a simultaneous increase in EMG amplitude and decline of the MPF (e.g. Basmaijan and De Luca 1985). Over the entire 1-hour task we observed a cumulative increase in perceived fatigue and EMG amplitude but not a consistent decrease in the MPF. Thus, the MPF decreased significantly over the 7 minutes of sustained activity but had returned to baseline values after each of the 3-minutes rest breaks. As expected, the participants differed considerably in fatigue manifestations, one reason being that the work load relative to maximal capacity differed between participants, since they were required to handle the same manipulandum.

Several previous studies investigating the recovery of MPF after a fatiguing exercise leading to decreased MPF have also found that this recovery is fast (e.g. Krivickas et al. 1996, Elving et al. 2002, Kuorinka 1988). MPF recovery was complete within minutes after short isometric contractions for the biceps muscle (Krivickas et al. 1996) and the lumbar muscles (Elving et al. 2002). Kuorinka (1988) showed that the MPF recovered within two minutes after a dynamic exercise of the biceps muscle at 15%MVC. In some of the intermittent arm abduction protocols investigated by Mathiassen (1993), EMG frequency recovered during rest breaks between isometric exercise bouts at 15-20%MVC, while EMG amplitude increased steadily over time in spite of breaks. It has been hypothesized that fatigue related changes in the EMG signal are caused by changes in intra- and extra-cellular K^+ and Na^+ concentration and that these metabolic changes will recover rapidly (e.g. Sjøgaard et al. 1988). However, long-term activities at low intensity have been suggested to require long recovery times of force generating capacity (e.g. Kroon and Naeije 1991). In the current study this is supported by the cumulative increase of perceived fatigue and EMG amplitude. This suggests that although the MPF has recovered quickly this does not necessarily mean that the force generating capacity has fully been restored within these 3-minutes breaks.

The increase in EMG amplitude observed during the course of the 1-hour work bout in our study might be explained by an additional recruitment of motor units (MU), necessitated by loss in the force-generating capacity of those already recruited (e.g. Moritani et al. 1986, Fallentin et al. 1993, Holtermann and Roeleveld 2006). Besides changes in the EMG amplitude caused by muscle fatigue, changes in timing strategy may also have contributed to the increased EMG amplitude at the end of the task. As shown in figure 6-7, timing strategies changed during the work bouts towards a shorter upward movement phase, and as a consequence of that movement speed and acceleration of the arm would probably have increased, which would be expected to be accompanied by an increased trapezius EMG level (Mathiassen and Winkel 1996, Sundelin 1993). However, due to longer waiting times the period of relative rest at the lower target, implying lowered EMG activity levels, also increased, which may have leveled out the work pace effect.

As commented in the introduction, previous studies on work-related manipulation activities requiring low or moderate force have shown inconsistent results regarding the relationship between perceived fatigue and EMG manifestations of fatigue. Although the results at the group level point towards such relationship, no association between these indicators of fatigue was established in the current study. As stated in an earlier study (Bosch et al. 2007), EMG measurements only reflect one of several possible contributions to perceived fatigue. While de Looze et al. (2009) suggested that motivation will have an influence on perceived fatigue; we could not in the present study see any significant relationship between perceived fatigue measured by the Borg CR-10 scale, and lack of motivation and sleepiness according to the SOFI inventory. Perceived fatigue during work may be more related to the effort needed to accomplish the task requirements, reflecting the relationship between those requirements and the individual’s instantaneous capacity (Madeleine 2010).

Fatigue, timing strategy and performance

Participants changed their timing strategy along the work bout; the waiting time at the upper target was significantly shortened at the end of the 1-hour task. From a biomechanical point of view this is an adequate response to increasing fatigue, since it will reduce the shoulder elevation moment produced by the mass of the arm, and thus lower the demand on the upper trapezius muscle. Participants also changed their strategy at the lower target within work blocks; the waiting time was longer at the end of each block. Furthermore, participants showed large inter-individual difference in waiting times at the start of the first work bout and the initial timing strategy was not related to the development of fatigue indicators. Thus, developing fatigue per se but not fatigue expectations seemed to trigger a motor adaptation with the intention of either preventing further fatigue or manage the work task as well as possible at the expense of further fatigue.

Changes in movement patterns of the upper extremity have been reported after enforced fatigue protocols in several tasks (e.g. Côté et al. 2002). Fuller et al. (2009) suggested that such kinematic changes reflect fatigue adaptation strategies with the purpose of reducing the load on the fatigued body region. In our rather constrained task such changes also occurred, but this was not sufficient to prevent perceived fatigue and development of fatigue manifestations in active muscles. Since repetitive work in an occupational setting usually allows for more temporal and spatial autonomy (e.g. discretionary micro breaks between consecutive work cycles, alterations in movement trajectories) the present findings can be generalized to “true” working life only with due caution.

A significant decrease in performance was found after one hour of the present repetitive work. As indicated by the positive error values (cf. Figure 6-8), participants reached the lower target too early. This might be explained by the shorter waiting time at the upper target: participants started their downward movement earlier and as a consequence of that arrived at the lower target too early.

In the upward movement direction, the gradually longer waiting times at the lower target within the work bouts did not result in pressing too late, as indicated by the positive error values. Participants showed a significant decrease in timing error at the upper target within work blocks. This apparent improvement of performance seems to a large extent be a consequence of hitting the target too early at the beginning of each work bout. This suggestion is supported by a moderate negative relationship between average waiting time at the lower target and timing error at the upper target (r= – 0.7), indicating that participants with longer waiting times arrived too late at the upper target. Thus, in both movement directions a change in timing strategy occurred together with decreased performance.

Whether this is a consequence of fatigue and/or an adaptation to counteract fatigue development could not fully be established from the present study, but the finding that a steeper rise in perceived fatigue was not associated with a larger drop in performance suggests that the former explanation may not be sufficient. In any case, the increasing effort spent in accomplishing the task, as indicated by the increasing EMG amplitude and maybe even by the increase in perceived fatigue, was not sufficient to maintain performance.

In summary, within work bouts clear manifestations of fatigue developed: EMG amplitude increased accompanied by a compression of the power spectrum towards lower frequencies, fatigue ratings increased, waiting times increased and the timing error decreased on the upper target. Across the six work bouts, EMG amplitude and perceived fatigue gradually increased, while EMG frequency did not change and performance decreased on both targets. Although the current study could not determine if these changes were causally related, the results suggest a relationship between fatigue development, altered movement and muscle activation strategies, and performance.

Fatigue, initial EMG activity, EMG variability and EMG amplitude ratio

It was hypothesized that individuals showing higher initial EMG amplitude would exhibit more prominent manifestations of fatigue, since they would be working at a larger proportion of their maximal capacity. For isometric exercise, the inverse relationship between relative force and endurance has been known for decades (e.g. Monod & Scherrer 1957, Rohmert 1973), and it has been confirmed in a multitude of studies, even on arm elevation (Mathiassen & Åhsberg 1999). In the present study, large differences between individuals were found in the initial (normalized) EMG amplitude, but it was not predictive of the development of fatigue according to our indicators. Likewise, our study could not confirm the relationship between the extent of variability in muscle activity and signs of fatigue shown in a few previous studies, if with other measures of variability than that used by us (e.g. Duchêne and Goubel 1990, Van Dieën et al. 1993, Palmerud et al. 1995, Van Dieën et al. 2009). Interestingly, however, EMG variability increased gradually during the work bout (cf. Figure 6-5), indicating a less consistent motor strategy with time and/or fatigue. An association can be expected between the level of EMG activity and its variability since force fluctuations are larger as more motor units are recruited (e.g. Moritz et al. 2005, Taylor et al. 2003).

Finally, the EMG amplitude ratio decreased within and across the work blocks. This might suggest an increase in movement efficiency. However as shown in figure 6-4, the effect is mainly caused by a large increase in the EMG amplitude during the upward movement.

The initial EMG amplitude ratio did not show any relationship with manifestations of fatigue. Earlier findings by Gerdle et al. (1989) and van Dieën and co-authors (1996) suggest that participants able to relax muscles during short periods in a work bout when relaxation is biomechanically possible will develop less fatigue, and we expected this to apply even among the present participants. One explanation that we couldn’t confirm the cited findings may be that the downward movement was not, in fact, a period allowing relaxation. The participant was forced to actively curb the manipulandum and steer it towards the lower target. According to our measurements, this led to a trapezius muscle activity corresponding to about 73% of that required when moving the manipulandum upwards.

Some other factors may also contribute to explaining the lack of associations between initial motor variables and fatigue development. First, our task was less constrained and performed at a lower intensity than that used in most previous studies, using mainly isometric or isokinetic contractions at moderate to high intensities. It might be hypothesized that the present dynamic task offered, in itself, so much opportunity for motor variability that the spontaneous additional motor variability was of marginal significance. Load sharing between synergistic muscles (Palmerud et al. 1995) or spatial redistribution within the trapezius muscle (e.g. Falla and Farina 2007) might have occurred but would be left undetected by the one pair of surface EMG electrodes used by us.

In the current study, the intensity level of the task itself was not normalized and therefore all participants performed the task at the same intensity level. Difference in muscle strength could thus be expected to be reflected in the EMG amplitudes, with weaker participants showing higher muscle activation. An association between EMG amplitude and fatigue development could thus be expected. However, EMG amplitudes were normalized using a reference contraction to reduce the effect of inter-individual differences not related to muscle activation, e.g. thickness of the subcutaneous fat layer (Mathiassen et al. 1995). Since the absolute exertion level of the reference contraction was similar between participants, apart from most likely minor effects of arm mass and length, normalization may also have masked strength differences between participants.

Practical conclusions

Even though the task in the current study was simulated and constrained, it did show similarities with short cycle assembly work in a driven production line (Bosch et al. 2007) and repetitive pick and place activities (Krawczyk and Armstrong 1991). Thus, some practical conclusions may, with due caution, be drawn on the basis of our findings with respect to similar settings in occupational life.

The current study demonstrated that during prolonged activities, even at moderate levels of exertion, performance can decrease. The performance indicator used in this study was timing error. While relatively small, errors of the present size might have serious consequences in occupational settings where great accuracy is required. If people have the opportunity to restore errors without affecting product quality (e.g. pick up dropped components) the overall effects might be negligible. However, correct movement timing is crucial in short-cycle line assembly and high risk environments offering no opportunities to restore errors. In these work situations, errors may have serious consequences, and therefore adjustments in motor behavior for the purpose of avoiding such errors might be implemented at the expense of increased fatigue.

Recent studies suggest that people adapt their motor behavior to fatigue so as to unload fatigued body regions (e.g. Fuller et al. 2009). The current study confirmed that the movement strategy may change but also that the change may not be sufficient to entirely alleviate fatigue. It might be hypothesized that the current constrained task did not allow sufficient motor variability in itself to effectively counteract fatigue. Whether similar occupational settings offer such opportunities to a wider extent, and whether such opportunities would then be utilized by the employees is an interesting issue for further research.

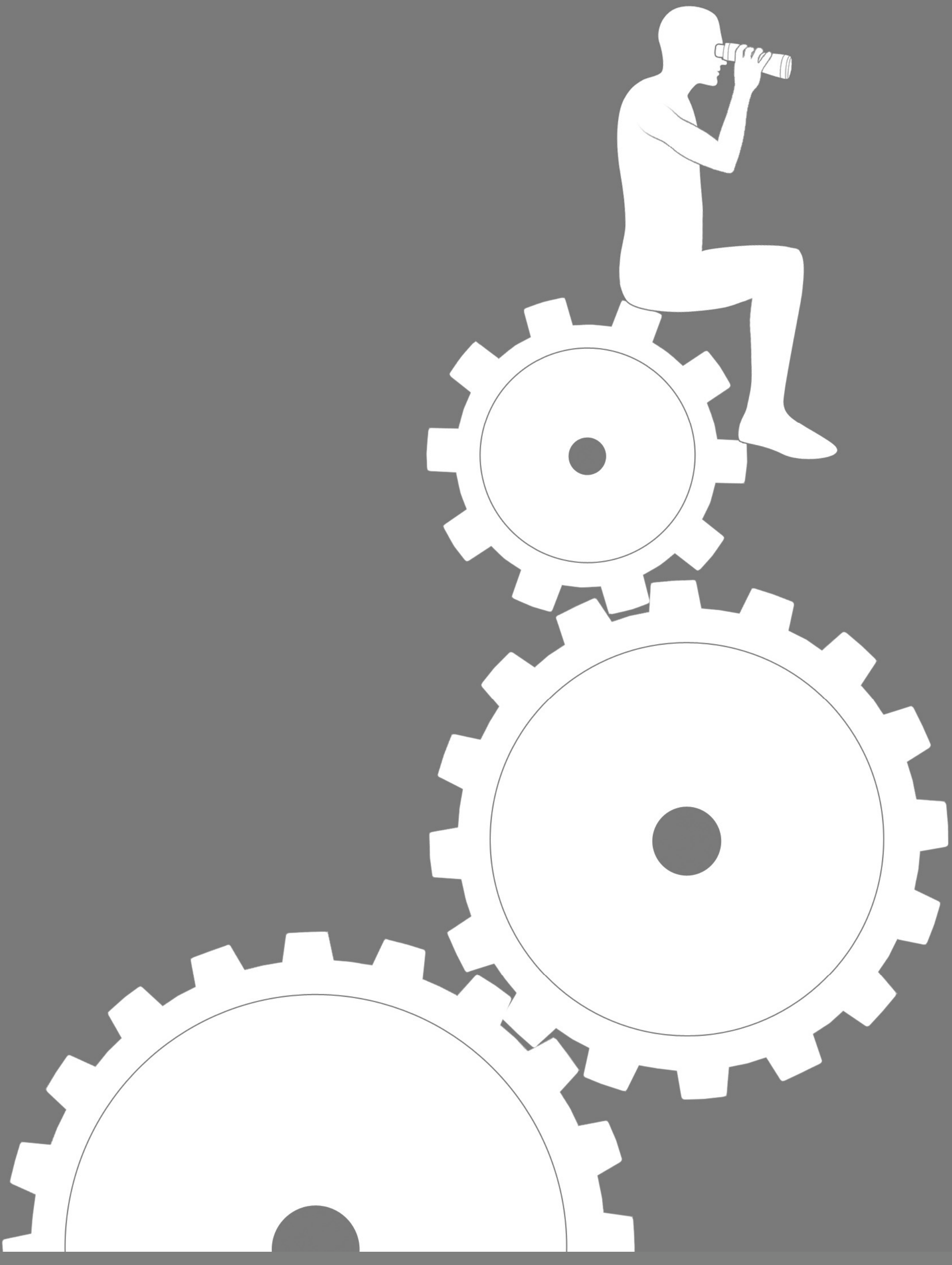
Finally, the absence of clear and sustained alterations in EMG MPF beyond the three minute rest breaks, in spite of persisting perceived fatigue and EMG amplitude, shed doubt on the universal usefulness of MPF as a fatigue indicator. In most industrial settings, technical disturbances and short interruptions (e.g. in order to supply materials) introduce periods with variation in load. These interruptions of work, which may otherwise lack variation might enhance recovery and possibly explain the weak accumulation of fatigue effects found in the present and other studies of repetitive work.

Acknowledgements

We would like to thank Göran Sandström for assistance in the data analysis and Suzanne van Mastrigt for helping with the illustrations of the experimental setup. This work was financially supported by the Centre for Musculoskeletal Research in Sweden and Body at Work, the Dutch Research Center for Physical Activity, Work and Health.

Chapter 7

General discussion and recommendations for future research



General discussion

In the general introduction, it was stated that occupational work often involves prolonged sustained low-force repetitive activities and a number of recent trends may further increase the prevalence of this type of work. Although force levels are relatively low, muscle fatigue or physiological signs of localized muscle fatigue may develop during low-intensity work. Localized muscle fatigue in the trapezius muscle may be a precursor of work-related upper extremity disorders and may reduce performance of employees. Localized muscle fatigue is usually defined as an exercise-induced decline in the maximal force or power capacity of the muscle (Bigland-Ritchie and Woods 1984). However, during low-force activities a reduction in force generating capacity does not necessarily occur while physiological changes affecting the capacity of the muscle do (e.g. Moussavi et al. 1989). To evaluate muscle fatigue electromyographic (EMG) indicators of fatigue are commonly used, i.e. a compression of the power spectrum towards lower frequencies accompanied by an increase in amplitude of the EMG signal (De Luca 1984, Basmajian and De Luca 1985).

The main objective of this thesis was, therefore, to determine how EMG manifestations of muscle fatigue and perceived fatigue develop during prolonged low-intensity occupational work. Furthermore, the relation between EMG indicators of muscle fatigue and perceived fatigue and the relation between manifestations of fatigue, performance and upper extremity kinematics were investigated.
In this section, after a short overview and discussion of the most prominent results, the final conclusions with regard to the aims are made and recommendations for future research are presented.

EMG manifestations of muscle fatigue development during low-force work

In **chapter 2** indicators of trapezius muscle fatigue were recorded over the course of 8 and 9.5-hours working days during low-force activities in two different manufacturing companies. Furthermore, locally perceived discomfort in the neck and shoulder region was rated. EMG indications of muscle fatigue were found in both companies in the first part of the shift. The EMG amplitude increased significantly, while a detailed analysis of the EMG frequency spectrum indicated shifts towards lower frequencies. Whereas EMG manifestations of fatigue were found in the first part of the shift, no significant changes were present during the lunch break or last part of the shift. The EMG manifestations of fatigue were more obvious in the company with higher intensities of work and large inter-individual differences were found. Ratings of perceived discomfort increased throughout the entire working day without significant recovery during the lunch break. The results presented in chapter 2 showed signs of fatigue. However, no significant correlation was found between objective and subjective manifestations of muscle fatigue.

To compare the results of this study to earlier reports, a literature review was performed and described in **chapter 3**. We retrieved 13 studies on objective measures of fatigue (including the study described in chapter 2). The studies included in the review investigated realistic low-force work tasks with a duration of more than 1 hour and an intensity level of less than 20%MVC for the mean or median trapezius activation level. Five studies analyzed fatigue development in the neck and shoulder region in an occupational site while eight studies were performed in a laboratory setting. All studies presented in the overview described in chapter 3, used surface-EMG to detect fatigue related changes in the upper trapezius muscle. EMG manifestations of fatigue, i.e. an increase in EMG amplitude accompanied by a decline of the MPF, were found in no more than 6 out of 13 studies.

From the review in chapter 3, load intensity appears to be a main factor differentiating studies detecting fatigue manifestations and studies that did not. Therefore, the effect of two 3-hours low-intensity occupational tasks (8 and 12%MVC) on the development of fatigue manifestations was investigated in **chapter 4**. Fatigue manifestations of the trapezius muscle were obtained from standardized EMG test contractions and EMG recordings during the task itself. Fatigue plots showed a combination of an EMG amplitude increase and a MPF decrease for most of the participants. The MPF showed a significant decrease over time at both intensities, while the highest intensity showed the largest reduction. On a group level no significant increase in EMG amplitude was found. These results confirmed the suggestion that large individual differences in EMG manifestations of fatigue exist. These individual differences may originate from different kinematic adjustment strategies during work. To verify whether participants would change their upper extremity posture or movements in relation to fatigue development, the upper extremity kinematics were recorded in chapter 5. Furthermore, changes in timing strategy, initial timing strategy and several EMG variables were studied as indicators of individual strategies to counteract fatigue in chapter 6.

In **chapter 5,** no EMG manifestations of fatigue were found during 2-hours simulated pick and place activities at two different work paces. However, perceived fatigue in the neck and shoulder region increased at both paces. Smooth and abrupt shifts of the shoulder posture and substantial cycle-to-cycle variability in wrist trajectory were demonstrated by participants during both work paces. These changes might have an alleviating effect on fatigue development.

In contrast to the results in chapter 5, clear manifestations of trapezius muscle fatigue were demonstrated during short-cycle reaching of the upper arm in **chapter 6**. In this experiment 7-minutes work bouts were followed by 3 minutes of rest for the total duration of 1 hour. An EMG amplitude increase was accompanied by a decline of the MPF during the work bouts. Over the entire 1-hour task, a cumulative increase in EMG amplitude was observed, but no significant decline was found for the MPF. The significant decline of the MPF during the active periods of work was counteracted by a fast recovery of the MPF during the imposed rest breaks. Perceived fatigue increased in the active work bouts. Recovery of perceived fatigue was shown by the participants during the breaks, but could not prevent a cumulative effect after 1 hour. Participants showed a change in timing strategy during the work bout and after 1 hour of work but this could not prevent the development of fatigue. However, participants with on average longer rest times showed a lower rate of perceived fatigue development. Other possible factors explaining individual differences in fatigue development like the initial EMG amplitude level, EMG amplitude variability and the ability to ‘relax’ the trapezius muscle were not correlated to the rate of fatigue development.

In conclusion, the results on EMG indicators of fatigue development in this thesis are variable. Chapters 2 and 6 showed an EMG amplitude increase accompanied by a decrease in the MPF whereas chapter 4 showed only a significant decline of the MPF. The results presented in chapter 5 did not show any significant EMG changes on a group level. The review of occupational fatigue studies presented in chapter 3 confirmed these variable results.

This thesis contributes to various explanations for these inconsistent results. First of all, most research efforts have focused on strictly controlled contractions. The relatively less constrained occupational activities at low intensities included in this thesis, might stimulate a higher level of motor variability, i.e. variability in kinematics, load sharing between synergistic muscles and shifts in activity between different compartments of the muscles. A high degree of motor variability might have a preventive effect on actual muscle fatigue development (McLean et al. 2001). Especially work with low-force requirements enables the opportunity for motor variation. As shown in chapters 3 and 4 load intensity seems to affect fatigue development. The tasks included in this thesis could, except from the task in chapter 6, be characterized as low-force activities. Earlier studies investigating muscle fatigue during high force contractions showed clear EMG manifestations of fatigue. However, at lower intensities, active motor units, while fatigued, may still able to sustain the required low forces, hence requiring no or minimal recruitment of additional motor units and thus no increase in EMG amplitude.

Furthermore, occupational work is in general characterized by the occurrence of incidental breaks or short periods of lowered activity. As demonstrated in chapter 6, short breaks support quick recovery of fatigue manifestations and might therefore mask the actual state of the studied muscles.

Finally, large inter-individual differences exist. As shown by the fatigue plots in chapter 2, a majority of the participants showed manifestations of muscle fatigue of variable magnitude. However, a few participants showed no fatigue effects. Although not reported in this thesis, fatigue plots were quite similar in the other studies. These individual differences may explain the less consistent results at a group level, while fatigue effects at an individual level are present.

A possible explanation for the large inter-individual differences can be found in individual adjustment strategies to counteract or delay muscle fatigue. Indications of changes in upper extremity kinematics and timing strategy were demonstrated during less constrained occupational work in chapters 5 and 6.

Surface EMG as a method to detect fatigue changes

From all fatigue studies presented in this thesis, we may conclude that the value of EMG manifestations of fatigue derived from bipolar EMG in (simulated) low-force occupational work is limited. This may be explained by a low sensitivity to the actual physiological changes in the muscle. At high force levels, the EMG amplitude and MPF are supposed to reflect additional motor unit recruitment and a decline of the conduction velocity (CV) of the fiber membranes of active motor units, respectively. However, at lower intensities these indicators of muscle fatigue may be less valid. Recently, Farina et al. (2006) showed that the MPF and EMG amplitude slopes were not significant different from zero, while the actual CV of individual motor units decreased. This implies that information derived from single motor units might be a more appropriate indicator of fatigue related changes than the globally detected surface variables.

Furthermore, a fast recovery of the MPF values as shown in chapter 6 might mask the actual state of muscles in the neck and shoulder region if not measured during the task itself. It has been shown that some muscles are subdivided in functional compartments (e.g. Mathiassen and Winkel 1990). Although this was not confirmed in chapter 4, topographical shifts in activity within and between muscle compartments (e.g. Holtermann et al. 2008, Jensen and Westgaard 1997) might limit the sensitivity of fatigue measures. As stated in the general introduction, the trapezius muscle is the most attractive muscle to study in the neck and shoulder region. In the current thesis all studies investigated changes in trapezius EMG except chapter 5 in which also the deltoid muscle and the carpi extensor digitorum were studied. Although the trapezius muscle is ideal for EMG studies, this does not necessarily mean that other, less superficial muscles in this body region (e.g. supraspinatus muscle) are less affected and may even limit performance before the trapezius muscle does.

Standardized EMG test contractions

Occupational work in industry is suggested to be dynamic and may therefore lead to erroneous interpretation of the EMG signals (Madeleine et al. 2001). Therefore, one may prefer standardized isometric test contractions (Suurküla and Hägg 1987) rather than EMG recordings obtained directly from the task itself. However, the effect of dynamic movements is relatively small for the trapezius muscle (Farina et al. 2002) and will be minimized during short-cyclic work by averaging work cycles (e.g. Nussbaum 2001).

In this thesis, test contractions were used in chapters 2 and 4. The test contractions used in chapter 2 partly demonstrated signs of fatigue. However, no direct comparison was made with EMG activity derived from actual work cycles. In chapter 4, the test contractions showed less convincing results than the fatigue indicators obtained from EMG activity during work. The fast recovery of EMG manifestations of fatigue (chapter 6) and the risk of recording a less representative motor unit activity (chapter 4, Blangsted et al. 2005) may explain the more clear results achieved when recording a number of representative work cycles. Besides the less reliable results, a temporal fatigue pattern could not be obtained from test contractions unless these are applied frequently in-between work cycles. Due to interruptions of work this is not feasible and therefore standardized test contractions are not recommend in industrial settings.

In conclusion, it’s recommendable to record EMG activity from a representative number of work cycles instead of test contractions in repetitive assembly work. The use of test contractions might mask actual fatigue effects, disturb daily routines in the production process and a number of work cycles offer the added advantage to evaluate cycle-to-cycle variability as a measure of motor variability. It gives preference to measure continuous or intermittent (i.e. before and after scheduled breaks) during a shift instead of capturing only data at the start and end because temporal development of fatigue is not always suggested to be linear.

Perceived fatigue or discomfort and its relation with EMG indicators of fatigue

Although EMG manifestations of fatigue were variable, a highly consistent increase in ratings of perceived fatigue or local discomfort was observed across all original and reviewed studies in this thesis.

No significant correlation between objective signs of muscle fatigue and perceived fatigue or discomfort was established in chapters 2, 3 and 6. The possible explanations for the absence of significant correlations have extensively been discussed in these chapters. In short, subjective feelings of local discomfort or perceived fatigue might be the result of other issues than muscle fatigue (e.g. work satisfaction, motivation of participants). This particularly holds for the evaluation of interventions in practice (chapter 2). EMG measurements, on the other hand, reflect only a small part of the physiological state of the muscle and bipolar electrodes cover a limited area of the surface of the trapezius muscle. EMG is therefore only one of the possible indicators of physical fatigue.

Although no significant correlation was found between perceived fatigue and EMG manifestations of fatigue, perceived fatigue may reflect the relation between the overall effort needed to accomplish the task requirements (i.e. an individual’s instantaneous capacity) and the actual work requirements of the job. Perceived fatigue ratings are therefore an important measure to evaluate interventions in real-life industrial settings.

Temporal aspects of work and the development of muscle fatigue manifestations

One strategy to delay muscle fatigue is the reduction of the intensity of the workload. This can be achieved by workplace adjustments. The workplace adjustments described in chapter 4 partly affected the manifestation of fatigue in the EMG signal. An improved workstation design, i.e. a lower working height and shorter reaching distances led to a lower MPF decrease. However, as already stated in the general introduction, load intensities are often optimized in industrial settings as a result of well-designed work stations. If so, modification of the temporal pattern of the load might be another valuable fatigue reducing intervention.

In the current studies the effects of temporal aspects of work were limited. The effects of a number of temporal aspects were evaluated in chapters 2, 5 and 6. An 1.5 hour extension of the working day did not lead to an additional increase in EMG fatigue manifestations or locally perceived discomfort towards the end of the day, as described in chapter 2. From an engineering point of view, it is interesting that the production output of the employees did not significantly drop during this 1.5 hour extension (not reported in this thesis). In chapter 5, no effect of work pace, determined by a predetermined time system, on EMG indicators of muscle fatigue and perceived ratings of fatigue was found.

In chapter 6, a clear effect of pauses on fatigue indicators was demonstrated. Although no direct comparison between different work-rest schedules was made in chapter 6, 3-minutes rest breaks promoted recovery of the EMG amplitude, MPF and perceived fatigue. On the other hand, the 30-minutes lunch breaks during the occupational activities in chapter 2 did not lead to significant recovery of EMG manifestations or perceived discomfort.

As proposed by the ‘size-principle’, low-threshold (type 1) motor units are recruited first (Henneman 1957) and remain constantly active during low-force activities. The muscle fibers which belong to these low-threshold motor units are supposed to be overloaded and fatigued as hypothesized by the ‘Cinderella hypothesis’ (Hägg 1991). Temporal interventions like periodic increases in activity might stimulate motor unit substitution within muscles (Westad et al. 2003) or shifts in activity to other muscle parts (e.g. Falla and Farina 2007) or muscles with similar biomechanical functions (e.g. Palmerud et al. 1998) and by that counteract fatigue effects. In this thesis, the modification of temporal aspects of low-force work activities did however not show clear effects on fatigue development. As stated earlier, it seems that the EMG methods used in the current thesis are not sensitive enough to detect these small changes at a motor unit level during occupational tasks.

Indicators of muscle fatigue and their relation to performance

In an industrial setting, short-term effects of fatigue on actual performance are as important as potential sick leave on the long term. As stated in the general introduction, the costs of reduced productivity as a consequence of disorders or experienced discomfort while at work almost equal the costs of sick leave (Blatter et al. 2005). The relationship between fatigue manifestations and practically relevant outcomes of performance were studied in chapters 5 and 6. The number of errors was not correlated to the rate of fatigue development, but work pace affected the number of errors as presented in chapter 5. In chapter 6, a decline in performance across time, expressed as timing error, was described. Performance seems to be affected by changes in timing strategy. Whether this is a result of adaptation to avoid or a consequence of fatigue remains unclear. Nevertheless, performance was negatively affected during highly repetitive sub-maximal work. The impact of reduced performance in real-life occupational activities depends on several issues, for instance the type of product or the applied production concept. The impact of errors is more serious when producing 'high-risk' products like the medical catheters as mentioned in chapter 2. Although errors do not have a fatal impact in some industrial settings, it seriously disturbs the production rate in serial flow or line production systems, where without buffers the work stations are strongly connected. Even if restoration of errors is possible, disturbance of the natural work rhythm may have a large impact on production line output.

New research technologies

The results in the current thesis suggest that the usability of bipolar surface-EMG to detect fatigue development during low-force contractions is limited. However, several non-invasive methods to detect physiological or fatigue-related changes in the neck and shoulder muscles do exist and might be appropriate for field evaluations in the near future.

(1). Recent studies suggest that the use of *mechanomyography (MMG)* provides complementary information to EMG during low-force isometric contractions (e.g. Madeleine et al. 2002). MMG is the recording of low-frequency vibrations generated by the lateral oscillations of active muscle fibers (Orizo 1993) and would represent the mechanical properties of a motor unit (Gordon and Holbourn 1948). However, recent studies showed only minor additional value of the MMG measurements during isometric contractions and to the authors' knowledge no attempts were made in more real-life dynamic activities.

(2). Localized muscle fatigue has been associated with a reduction in microcirculation and a decline in oxygen availability during high-force contractions. The *Near Infra-Red Spectroscopy (NIRS)* may provide useful information about metabolic changes and local blood flow in the muscle during work. This non-invasive method has been used for the monitoring of changes in blood volume, oxygenation and hemodynamics (e.g. Flodgren et al. 2009). Recent studies showed contrasting results for several muscles during low-force contractions. Flodgren et al. (2006), van Dieën et al. (2009) and

Callaghan et al. (2010) found no or only very small (Lin et al. 2010) decreases in oxygenation during sustained low-force contractions while for example Crenshaw et al. (2006) demonstrated temporal effects. Poor correlations with discomfort scores were found by Callaghan et al. (2010). In conclusion, NIRS might be a useful alternative technique to broaden the understanding of muscle physiological changes during low-force upper extremity activities. Recent development enables quantitative measurements with high time resolution. However, the application of NIRS to detect fatigue related changes in industrial activities of low- to moderate intensity is up to now limited. Furthermore technical limitations (e.g. noise due to changes in posture or movements of the probes) at the initiation of the contraction) may result in less reliable results in dynamic industrial settings especially when measured during work.

(3). Promising developments have been made in *multi-channel surface EMG*. Two-dimensional EMG arrays have proven to be of additional value compared to the traditional bipolar surface EMG. The arrays have been used to detect shifts in muscle activity (e.g. Falla and Farina 2007) and allow motor unit decomposition from non-invasive methods (e.g. Gazzoni et al. 2004, van Dijk et al. 2009) in constrained and isolated settings. The application of multi-channel arrays is, however, time-consuming and relatively sensitive to disturbances and therefore not yet appropriate for dynamic and unpredictable environments. Recent developments increase the potential of using these electrodes in real-life work. The electrode technology itself has been improved as shown by Lapatki et al. (2004). Thinner, more flexible and easier attachable electrodes allow better recordings of EMG data from relevant shoulder muscles. Furthermore, motor unit decomposition algorithms have been strongly improved in the last decade (e.g. Kleine et al. 2008). In the near future, this technique may allow detection of fatigue related changes in motor unit activity in simulated and real-life occupational settings.

As shown in chapters 5 and 6, capturing kinematics provides insight in postural changes or changes in working strategy triggered by fatigue development. However, recording upper extremity kinematics during occupational work on a larger scale is time- consuming and therefore expensive (e.g. Trask et al. 2007). Recent developments to capture objects with the assistance of video-based marker tracking technology (Lepetit and Fua 2005) and the use of inertial and magnetic measurement systems (e.g. Zhou et al. 2008, de Vries et al. 2010) might solve these problems in the near future. Future developments should focus on ambulatory systems that combine motion capturing and high-density surface EMG to further evaluate the effects of temporal interventions during low-force work.

The current thesis includes papers investigating the effects of work requirements and muscle fatigue on performance in an experimental setting. Besides the technological improvements to detect muscle fatigue as described above, future research and interventions in industry should focus on more than health and safety issues only. Dul and Neumann (2009) recently suggested that the impact of ergonomics will be enlarged if ergonomists contribute to the company strategy and business goals. One of the focuses of research should therefore be on the interaction between health and performance to improve the evaluation of working conditions in a design or operational phase. One example of an application integrating company business goals and human factors in manufacturing might be the use of enhanced simulation models. So far, simulation models primarily focused on system performance and generally treat the operator as a non-fatiguing element with infinite endurance time. On the other hand, dynamic muscle models (e.g. Ma et al. 2009) have been focusing on the human without taking into consideration the effects on the environment. Integration of both approaches, i.e. predict system performance and work load on the operators may improve working conditions and strengthen business performance.

Conclusions

The conclusions with respect to the research aims as mentioned in the general introduction are:

- Performing a low-intensity occupational work task leads to perceived fatigue development in the neck and shoulder region, partly supported by EMG manifestations of trapezius muscle fatigue. The variable outcomes of EMG manifestations of fatigue seem to be a result of a large motor variability and individual variation in less constrained occupational tasks.

- During unconstrained industrial work the sensitivity of bipolar surface-EMG to detect fatigue related changes in the upper trapezius muscle is limited.

- EMG manifestations of trapezius muscle fatigue are not correlated to ratings of perceived fatigue or feelings of local discomfort and the extent of muscle fatigue development can not be predicted by initial levels of muscle activity, variability in muscle activity or timing strategy.

- Frequent short rest breaks have a positive effect on fatigue development in the neck and shoulder region whereas longer lunch breaks do not lead to significant recovery of perceived fatigue and EMG manifestations of fatigue.

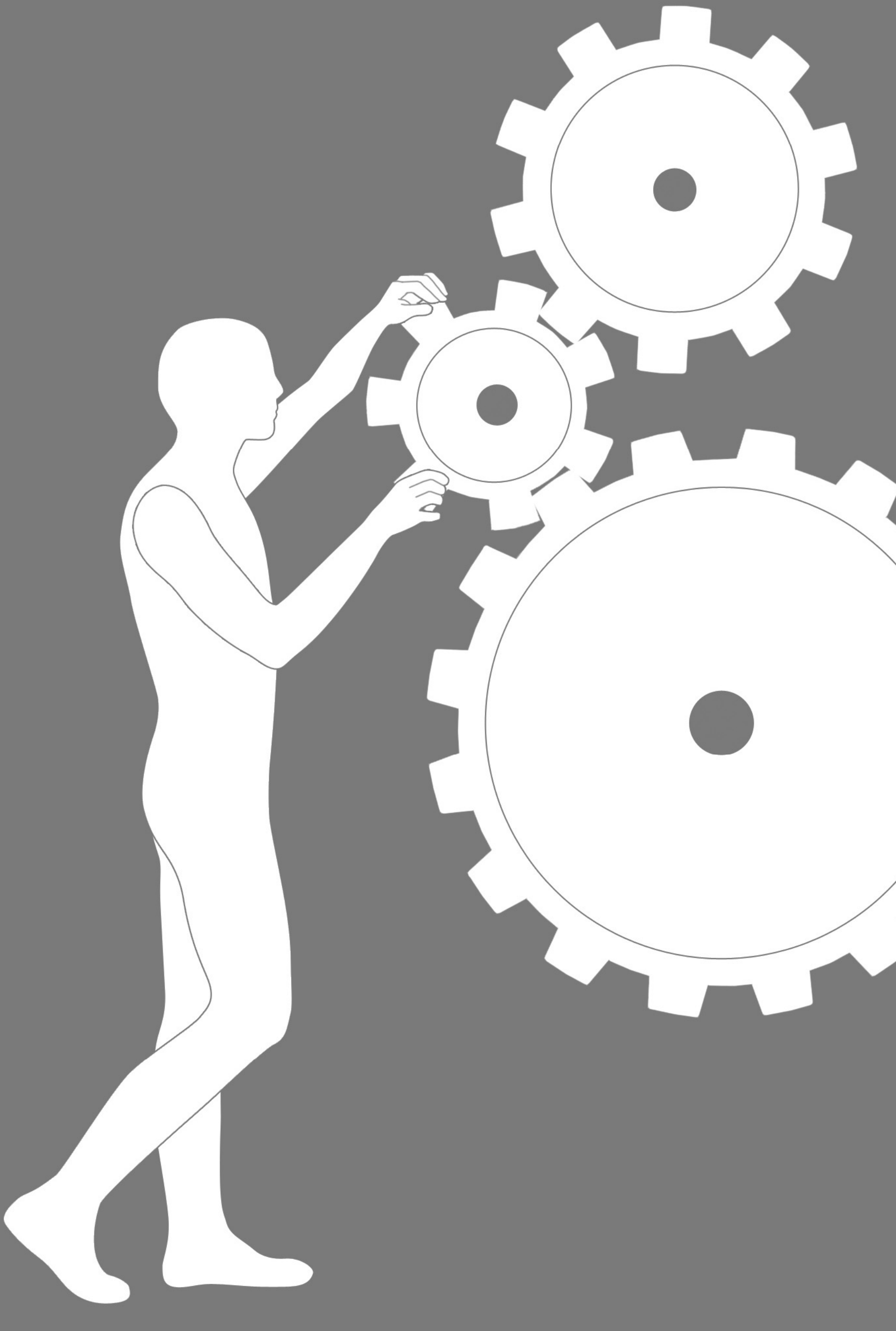
- A work day extension of 1.5 hours does not cause additional fatigue development compared to a regular 8 hours working day. Extended working days at the end of a working week do not differ from the first day of the week with respect to fatigue development.

- When comparing a normal pace with a realistic manufacturing pace, a 26% higher work pace does not have a negative effect on fatigue development but almost doubles the number of errors.

- In unconstrained occupational repetitive work, people spatially and temporally adjust their upper extremity kinematics, most likely to counteract fatigue development. Temporal adjustments may negatively affect performance during repetitive low-force work activities.

Chapter 8

Practical recommendations for optimizing repetitive industrial assembly work



Practical recommendations

Work intensity in repetitive industrial work is often low (i.e. low muscle forces in combination with highly repetitive movements) and lowering intensities does not seem to be the most effective measure to optimize work conditions. Modification of the temporal structure of work or more specific temporal variation in workload to trigger or enhance motor variation in individual operators is a key issue to counteract muscle fatigue development and improve operator performance. In this context, Winkel and Westgaard (2001) introduced the term exposure porosity. Work needs to be sufficient porous i.e. allow the occurrence of short pauses and restorative work.

Although the effects of variation in work load were not explicitly investigated in this thesis, our findings suggest that variation is important; i.e. a large extent of spatial and temporal motor variability in less constrained occupational tasks may counteract fatigue development.

A recent literature review of Nordander et al. (2009) confirmed the widespread notion that physical variation at work is important by showing elevated risks of musculoskeletal problems in repetitive occupational work, when comparing constrained to less constrained work. Furthermore, a recent study of Luttmann et al. (2010) suggested that a higher degree of self-organization of work (e.g. by changing working posture, work pace or sequence of tasks) resulted in a decrease of muscular activation over the course of a working day. This decrease in muscular activation caused by more variation in work load was related to less acute muscular complaints.

From an engineering perspective, process variance should be minimized to optimize business performance. However, introducing variation in workload does not necessarily mean that process variance should increase. In an industrial setting, work load variation can be introduced at different interacting levels (e.g. production system design, temporal organization of work and its supply chain, work station and product design). In the following paragraphs a few examples of how to achieve this, are given for different levels.

Production system design

In manufacturing different production system configurations exist. Two extreme variants are serial flow production lines and parallel work cells or dock assembly. In serial flow production lines with or without intermediate buffers, operators perform short-cycle assembly activities at consecutive work stations. In parallel work cells, a complete product is manufactured by one individual or team (e.g. Kadefors et al. 1996, Neumann et al. 2006). Shop-concepts in which operators are moving along the line instead of the product or hybrid systems, in which serial and parallel work stations are integrated, are two examples of alternative configurations.

Parallel work cells or shop-concepts, are suggested to be the most optimal production concepts for variation in work load. However, the current trend in manufacturing is towards a more intensive line approach with more frequent short-cycle tasks although balance losses, vulnerability to disturbances and difficulty handling all product variants are well recognized problems of a rigid line approach (Neumann et al. 2002, Neumann et al. 2006). One of the main drivers for this shift is partial automation of production systems. Automated or semi-automated production systems reduce variation in work load by leaving only residual tasks and more strictly paced work.

Several other factors, like the type of product, product variety and volumes, learning times, equipment investments (e.g. tooling), labor market and organizational culture contribute to the choice between production systems. Work load and more specifically the variation in work load are important but often neglected factors. It is recommended to seriously take into account the factor variation in work load when designing new or modifying existing production systems. If a production system configuration does not offer sufficient variation to operators, it is recommended to implement additional measures to increase variation in work load. Some examples of how to achieve this are described below.

Temporal work organization: rest breaks and variation in activities

As stated above, low-force manual work needs to be sufficiently porous i.e. allow the occurrence of short breaks or restorative activities. Scheduled breaks had contrasting effects on fatigue manifestations in the current thesis. Earlier studies confirmed these inconsistent results on performance and physiological manifestations of fatigue. Guidelines for the number and frequency of breaks are not available at the moment and it might be questionable if those will be available in the near future. Beside these scheduled breaks, tasks should allow opportunities to take short rest moments or micro breaks and those should be integrated in the production system routines. Mclean et al. (2001) contributed evidence that the implementation of micro breaks has no detrimental effect on worker productivity. However, a recent study by Dempsey and co-authors (2010) suggested that operators do not always use the opportunity to rest; operator’s finished their jobs without small breaks in self paced or batch type production. This might be explained from already learned motor patterns or disturbance of a preferred individual production rhythm (e.g. Hagberg and Sundelin 1989). It is therefore recommended to introduce short-periods of rest within production routines (e.g. quality control or testing) in addition to scheduled breaks.

The greater part of rest breaks described in literature and observed in companies are typically non-productive. In addition to rest breaks, monotonous work could be interrupted by short periods of time were other activities are performed to support the relaxation of tissue. This may result in good ergonomics and good economics.
To reduce fatigue and enlarge work load variability, periodic increases in load seems to be successful (e.g. Mathiassen and Turpin-Legendre 1998, Falla and Farina 2007). As suggested in chapter 5, lifting heavier parts during low force work might have alleviating effects on fatigue and performance. Additional activities with a higher intensity, which should not necessarily be seen as non-value added from an engineering perspective, can be implemented within or after a fixed number of work cycles. However, it is the challenge to find and integrate activities that promote task diversity.
Periodic supply of an operator’s work station using smaller storage bins was found to be effective in forcing workers to interrupt their monotonous assembly work and reduce discomfort (van Rhijn et al. 2005). Furthermore, the implementation of irregular activities of short duration and moderate load may support variation in working posture (Mathiassen and Winkel 1996). For instance, the opportunity to reach incidentally above shoulder level, manual transportation of finished goods within or between work stations or cleaning one’s own work station in between production orders.
Beside recent trends in manufacturing and distribution (e.g. return to Tayloristic principles) that increase the need for variation, other trends like adding more value-added services to order pick stations or growing levels of customization and shorter product lifecycles resulting in smaller order and batch sizes and a larger product variety, might stimulate work load variability.
This variety of products is often manufactured at so-called mixed-model lines which might stimulate variation; e.g. opportunities for a short break at the start of a new order, the use of different tooling and more different parts and components that need to be assembled. These different parts can be stored within work stations and thereby increase variation or can be stored at specific warehouse locations close to the work station which also introduce additional opportunities for variation in working posture.

In addition to more load variation within tasks or work stations, job rotation or enlargement at a system level is often associated with positive effects on work load variability (e.g. Möller et al. 2004). However, job rotation usually requires a more complex organization of work. Implementation of rotation within production routines might be more successful and is therefore recommended. Organizational measures like alternating pause schemes (de Looze et al. 2010) or the self-balancing line concept of ‘flexing’ between different workstations (e.g. Tuinzaad et al. 2008) are just two examples of how to achieve this. These interventions primarily aim at a reduction of line imbalance, additional system output and the reduction of lead times but may automatically stimulate work load variability; workers are forced to change work station as a consequence of work organization principles. However, variability in load will only be maximized as load patterns and activities with different work intensities are included (Fernström and Åborg 1999) and different body parts are alternately loaded (Henderson 1992).

Temporal work organization: work pace variation

Work pace is associated with the health of workers (Houtman et al. 1994) and system performance (Wells et al. 2007). However, quantitative ergonomic guidelines about work pace are lacking. In manufacturing industries, it is common use that the work pace is based on calculations (e.g. predetermined time systems like MTM) in which human factors (e.g. fatigue development or the degree of arm lifting) and variation in pace are insufficiently addressed. To increase temporal variation in work load, cycle-to-cycle variability in work pace should be possible. A predetermined pace could thereby be used to determine the average work pace. To enlarge variability in work pace, the enlargement of the total cycle time in line assembly (e.g. assemble a tray of four products instead of one) might be useful as a potential fatigue and error limiting measure. Organizational measures like flexing between work stations may even be more effective. Cycle-to-cycle variability within and between operators is possible without affecting the work flow and by that the overall system performance.

Workstation and product design

The current thesis showed that operators used different work techniques or temporal movement strategies to perform the same task. Work station and product design should therefore allow different work postures, techniques and individual preferences to increase cycle-to-cycle variability.

For instance, an industrial engineering method like the ‘Design for Assembly’ approach simplifies assembly procedures and thereby supports operators in zero-defect assembly (e.g. Wells et al. 2007). However, this does not necessarily mean that components are fastened using stereotyped movements with low variability. A recent study by Wells et al. (2010) demonstrated that alternating different grips (e.g. a power and a pulp pinch grip) with to a larger extend functional similarity resulted in a more diverse exposure.

***Figure 8-1**. Work station design can stimulate variation in workload and thereby reduce fatigue and stimulate performance. Decentralizing bin locations of product specific components force operators to change working posture.*

A more flexible work station design, allowing sitting, standing or supported-standing may stimulate variation in upper extremity postures. Furthermore, work stations with only centrally positioned bins for standardized parts and more decentralized locations for order-specific components stimulate variation in working postures and movements (Figure 8-1).

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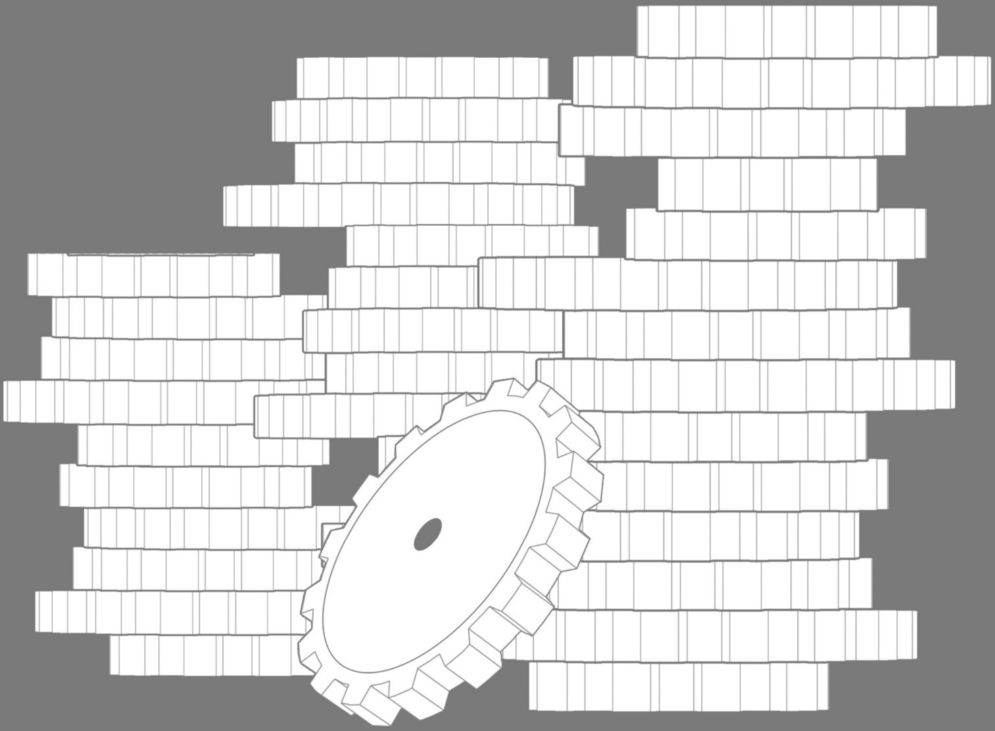

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Samenvatting

Vermoeidheid en prestatie tijdens laagintensief industrieel werk

Vermoeidheid en prestatie tijdens laagintensief industrieel werk

Het aantal mensen dat repeterende werkzaamheden met een lage intensiteit en met weinig variatie verricht is nog steeds aanzienlijk. Diverse trends dragen hieraan bij: het verplaatsen van activiteiten naar lagelonenlanden, de automatisering van productiesystemen, de doorvoering van lean manufacturing principes en de verdere invoering van ICT. Laagintensief werk wordt gekenmerkt door activiteiten waarbij de gemiddelde fysieke belasting laag is. De krachtuitoefening van nek- en schouderspieren bedraagt vaak niet meer dan 15 procent van de maximale capaciteit. Bovendien is de variatie in belasting laag. Het solderen en assembleren van scheerapparaten (Figuur 1a), het monteren van noodverlichting of koffiezetautomaten en het verzamelen van orders op compacte stationaire werkplekken (Figuur 1b) zijn enkele voorbeelden van het type werk dat in dit proefschrift centraal staat.

***Figuur 1**. Voorbeelden van werkzaamheden met een lage intensiteit. Het monteren van scheerapparaten (links) en het verzamelen van orders op compacte order-pick werkplekken (rechts).*

Ondanks de lage intensiteit van het werk zijn er aanwijzingen dat spiervermoeidheid en ervaren ongemak gedurende de werkdag kunnen toenemen, met een verandering van bewegingspatronen of de timing van beweging en een mogelijke afname van prestatie als gevolg. Naast deze korte termijn effecten, met mogelijk grote financiële consequenties, zijn er aanwijzingen dat het optreden van spiervermoeidheid op langere termijn lichamelijke klachten en verzuim kan veroorzaken. Spiervermoeidheid kan gedefinieerd worden als een afname van de maximale kracht die iemand kan leveren. Bij laagintensieve spiercontracties is een afname van de maximale kracht minder waarschijnlijk, maar er kunnen wel fysiologische veranderingen plaatsvinden die de capaciteit van een spier negatief beïnvloeden. Spiervermoeidheid of fysiologische veranderingen in spieren die met vermoeidheid samenhangen kunnen o.a. bestudeerd worden met behulp van electromyografie (EMG). EMG-indicatoren van vermoeidheid worden gekenmerkt door een toename van de amplitude van de spieractiviteit en een verschuiving in de frequentie-inhoud van het signaal naar lagere frequenties. Diverse werkgerelateerde factoren kunnen de vermoeidheidsontwikkeling en de prestatie beïnvloeden. Bij laagintensief werk zullen vooral de tijdsgerelateerde kenmerken van het werk (bijvoorbeeld werkduur, werktempo en pauzes) effect hebben op het verloop van vermoeidheid en prestatie. Het verlagen van de intensiteit lijkt bij dit type werk minder effectief, de intensiteit van de belasting is immers al laag.

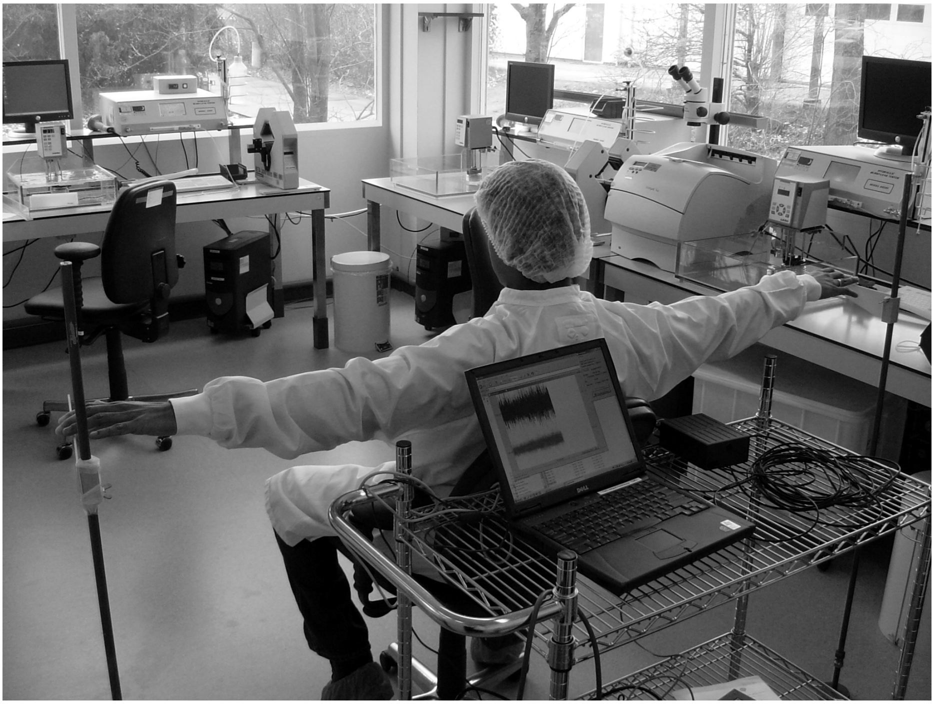
In **hoofdstuk 1** wordt een conceptueel model gepresenteerd waarin de veronderstelde samenhang tussen blootstelling aan taakeisen en de acute respons door medewerkers (vermoeidheid, prestatie en beweging) wordt weergegeven. De invloed van psychosociale factoren (o.a. autonomie in het werk) is in dit proefschrift buiten beschouwing gelaten.

In dit proefschrift stonden de volgende vragen centraal tijdens de bestudering van laagintensieve taken:

- Hoe ontwikkelen EMG-indicatoren van vermoeidheid en ervaren vermoeidheid zich tijdens arbeid met een lage intensiteit?
- Welk effect hebben werkduur, werktempo en pauzes op het verloop van vermoeidheid?
- Hoe verhouden objectieve maten van spiervermoeidheid (EMG-indicatoren) zich tot subjectieve beoordelingen (ervaren ongemak of vermoeidheid)?
- Wat is het effect van vermoeidheid op prestatie, houding en beweging tijdens dit type werk?

Om antwoord te kunnen geven op de bovenstaande onderzoeksvragen zijn verschillende experimentele studies uitgevoerd. In **hoofdstuk 2** wordt allereerst een veldonderzoek beschreven waarin indicatoren van vermoeidheid zijn gemeten tijdens normale (8 uur) en verlengde (9,5 uur) werkdagen. In twee Nederlandse productiebedrijven, die respectievelijk scheerapparaten en katheters produceren, is het ervaren ongemak in de nek- en schouderregio gedurende de dag bevraagd. Het EMG in de m. trapezius pars descendens werd tijdens een referentiecontractie geregistreerd op verschillende tijdstippen op de werkdag (Figuur 2). In het eerste gedeelte van de werkdag waren vermoeidheidseffecten zichtbaar in het EMG (een toename van de EMG-amplitude en een afname van de frequentie-inhoud) en nam ook het ervaren ongemak in de nek en schouders significant toe. In het tweede gedeelte van de werkdag werden geen effecten gevonden in de EMG-indicatoren van vermoeidheid, terwijl medewerkers wel een significante toename in het ervaren ongemak rapporteerden. De lunchpauzes leidden niet tot significant herstel van vermoeidheid. Het verlengen van de werkdag met anderhalf uur leidde niet tot additionele spiervermoeidheid, maar wel tot een evenredige toename in productieoutput. Vermoeidheidseffecten leken sterker bij het werken met een hogere intensiteit, maar grote interindividuele verschillen waren zichtbaar in alle vermoeidheidsmaten. Objectieve en subjectieve indicatoren van vermoeidheid bleken niet significant gecorreleerd.

Om de uitkomsten van de studie in hoofdstuk 2 te vergelijken met eerder onderzoek naar vermoeidheidseffecten, is een literatuuronderzoek uitgevoerd en beschreven in **hoofdstuk 3**. In totaal dertien artikelen beschreven het verloop van vermoeidheid gedurende minimaal 1 uur, waarbij de spieractiviteit maximaal 20 procent van de maximale capaciteit bedroeg. In alle studies werd gebruikt gemaakt van EMG-metingen om vermoeidheidsverandering te detecteren. In slechts zes van de dertien onderzoeken werd een toename van vermoeidheid vastgesteld op basis van EMG-indicatoren, terwijl een toename van ervaren vermoeidheid in alle onderzoeken werd aangetoond. De intensiteit van de taak was de enige factor die van invloed bleek op het al dan niet optreden van spiervermoeidheid.



Figuur 2*. De referentiecontractie, zoals gebruikt in hoofdstuk 2 en 4, om electromyografie op een gestandaardiseerde wijze te meten.*

Om het effect van intensiteit verder te onderzoeken zijn in **hoofdstuk 4** twee laagintensieve assemblagetaken (Figuur 3a) bestudeerd, waarbij de intensiteit tussen beide taken verschillend was. EMG werd gemeten tijdens de taakuitvoering en tijdens de eerder genoemde referentiecontractie. Het merendeel van de tien deelnemers vertoonde objectieve tekenen van vermoeidheid tijdens beide taken. Op groepsniveau bleek de frequentie-inhoud van het signaal een niet-lineaire afname te vertonen, waarbij het effect sterker was voor de conditie met de hoogste intensiteit. De amplitude van het EMG-signaal bleek op groepsniveau, in tegenstelling tot de frequentie-inhoud, niet te veranderen in het verloop van de tijd. Tijdens de taak gemeten EMG-indicatoren bleken een meer consistent beeld te geven dan de resultaten van de referentiecontracties. Ook in dit onderzoek werden grote verschillen tussen personen vastgesteld en werd de suggestie gewekt dat temporele veranderingen in bewegingstrategie een mogelijke verklaring konden vormen voor deze individuele verschillen.

In **hoofdstuk 5** is daarom onderzocht in welke mate de kinematica van de bovenste extremiteit (schouder, elleboog en pols) veranderde tijdens een 2 uur durende assemblagetaak (Figuur 3b) en is bekeken of dit beïnvloed werd door het werktempo. De ervaren vermoeidheid nam significant toe tijdens beide werksnelheden, maar een verandering in EMG-indicatoren van spiervermoeidheid, gemeten in twee nekschouderspieren (m. trapezius pars descendens en m. deltoid anterior), was niet zichtbaar. Werktempo bleek geen effect te hebben op vermoeidheidsontwikkeling, maar handelingen werden wel efficiënter uitgevoerd tijdens het hoogste werktempo. Bovendien vertoonden de acht deelnemers geleidelijke en abrupte veranderingen in schouderpositie en bleek de afgelegde weg van de pols sterk te variëren tussen de afzonderlijke cycli.


a. **b.**

***Figuur 3**. **a**. De opstelling waarmee het effect van taakintensiteit op vermoeidheidsontwikkeling is onderzocht in hoofdstuk 4. **b**. In hoofdstuk 5 is het effect van werktempo op vermoeidheidsindicatoren en kinematica onderzocht tijdens assemblagewerkzaamheden.*

Of er naast spatiële veranderingen ook temporele veranderingen (in timingstrategie) plaatsvonden, is in **hoofdstuk 6** onderzocht. Achttien deelnemers voerden gedurende 7 minuten repeterende armheffingen uit tussen twee posities op elleboog- en schouderhoogte. Periodes met armheffingen werden afgewisseld met 3 minuten rust en dit werd zes keer herhaald, waarbij de totale duur van de studie dus 1 uur bedroeg. De wachttijd en de afwijking in timing ten opzichte van het opgelegde tempo werd op beide posities voor iedere cyclus bepaald. EMG werd afgeleid van de m. trapezius pars descendens. Ervaren vermoeidheid werd voor én na ieder blok met repeterende belasting beoordeeld. Over de gehele werkperiode van 1 uur was een toename in ervaren vermoeidheid en objectieve vermoeidheid (aanwezigheid van EMG-indicatoren) en een toename in variatie in EMG-amplitude zichtbaar. Tijdens de perioden met repeterend werk veranderden de deelnemers hun bewegingsstrategie; er werd langer gewacht op de laagste positie. De 3 minuten durende pauze leidde tot herstel van vermoeidheid, maar kon niet voorkomen dat de vermoeidheid na 1 uur was toegenomen. Bovendien nam de prestatie af: zowel binnen de blokken met repeterende belasting als na 1 uur werk nam de afwijking in timing significant toe. Objectieve en subjectieve indicatoren van vermoeidheid vertoonden geen significante correlaties. Bovendien was de ervaren fysieke vermoeidheid niet significant gecorreleerd aan aspecten van ervaren mentale vermoeidheid, zoals een gebrek aan motivatie. Er werden geen significante correlaties gevonden tussen factoren die mogelijk de grote interindividuele verschillen in vermoeidheidsontwikkeling kunnen verklaren (o.a. initiële strategie, initiële EMG-amplitude, variatie in EMG-amplitude en amplitude ratio).

De belangrijkste conclusies van dit proefschrift zijn:

- Laagintensief werk leidt tot een toename van de ervaren vermoeidheid in de nek- en schouderregio. Dit wordt deels ondersteund door EMG-indicatoren van spiervermoeidheid.

- De minder consistente resultaten in de EMG-uitkomsten tijdens realistische laagintensieve taken worden waarschijnlijk veroorzaakt door een grote mate van variatie in houding en beweging en door het snelle herstel van vermoeidheidsindicatoren tijdens korte onderbrekingen van het werk. Realistische productiewerkzaamheden bieden mogelijkheden om van werkhouding te veranderen of kort te pauzeren (bijvoorbeeld tijdens storing of opstarten nieuwe order). Bovendien lijkt de gevoeligheid van bipolair oppervlakte EMG en de gekozen vermoeidheidsindicatoren (verandering in amplitude en frequentiespectrum) beperkt voor het detecteren van vermoeidheidsgerelateerde veranderingen in nek- en schouderspieren tijdens werk met een laag krachtsniveau. Het gebruik van 2-dimensionale High Density EMG-matjes kan in de nabije toekomst tot verbeterde inzichten leiden, aangezien met deze methode fysiologische veranderingen in de spier op motor-unit-niveau geanalyseerd kunnen worden.

- Het verdient de voorkeur om EMG-indicatoren van vermoeidheid af te leiden uit een aantal representatieve cycli tijdens repeterend industrieel werk. Het gebruik van gestandaardiseerde isometrische referentiecontracties kan mogelijke vermoeidheidseffecten maskeren en bovendien kan met spieractiviteit, gemeten tijdens de taak, een uitspraak worden gedaan over de mate van EMG-variabiliteit; de mate van variatie in belasting.

- Onder verschillende omstandigheden (lab- en veldstudies met verschillende taken) werd geen significante correlatie gevonden tussen EMG-indicatoren van vermoeidheid en de gerapporteerde ervaren vermoeidheid van medewerkers. Mogelijke verklaringen voor de afwezigheid van een significante relatie kunnen liggen in het feit dat, met name in interventiestudies, ervaren vermoeidheid of ongemak door meer factoren wordt beïnvloed dan alleen spiervermoeidheid (bijvoorbeeld motivatie of tevredenheid). EMG-metingen daarentegen weerspiegelen slechts een klein gedeelte van de fysiologische toestand van de spier. Tijdens de evaluatie van interventiestudies zijn beide echter bruikbaar en geeft ervaren vermoeidheid een goed beeld van de mate waarin aan de taakeisen kan worden voldaan.

- Tijdens langdurig repeterende werkzaamheden met een beperkte krachtuitoefening, zijn veranderingen in de houding en beweging van de bovenste extremiteit zichtbaar. Dit lijkt een mogelijke strategie om vermoeidheidsontwikkeling te doorbreken, maar heeft een mogelijk negatief effect op prestatie.

- Frequente korte onderbrekingen kunnen de ontwikkeling van vermoeidheid in de nek en schouders onderbreken en leiden tot herstel in ervaren vermoeidheid en in de EMG-indicatoren van vermoeidheid. De langere lunchpauzes leidden niet tot significant herstel van vermoeidheid.

- Het verlengen van de werkdag met 1,5 uur leidde niet tot additionele vermoeidheidsontwikkeling in vergelijking tot een normale 8-urige werkdag.

- Een werktempo dat meer dan 25 procent hoger ligt, heeft geen negatief effect op vermoeidheidsontwikkeling. De kwaliteit van het werk wordt echter wel negatief beïnvloed; het aantal fouten verdubbelt wanneer een hoog tempo vergeleken wordt met een normaal werktempo.

Wat betekent dit voor de praktijk?

In **hoofdstuk 8** worden verschillende aanbevelingen gedaan om de vermoeidheidsontwikkeling tijdens laagintensief werk te doorbreken en mogelijk prestatieverlies te beperken. Aangezien de gemiddelde krachtsniveaus tijdens het werk al laag zijn, is het verder verlagen van krachtsniveaus waarschijnlijk niet de meest effectieve oplossing. Om vermoeidheidsontwikkeling te beperken is het vergroten van de variatie in belasting een van de mogelijke oplossingen. In een productieomgeving wordt de variatie in belasting bepaald door verschillende factoren op verschillende niveaus. Allereerst is de keuze van het productiesysteem van invloed. Daarnaast wordt belastingvariatie bepaald door pauzes, taakverbreding, taakroulatie, werksnelheid, product en werkplekontwerp. Praktische handvatten voor het vergroten van variatie in productiebedrijven worden aan het einde van dit hoofdstuk beschreven.

About the author

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Tim Bosch was born on October 7th 1979 in Warmenhuizen, The Netherlands. In 1998, he finished secondary school (CSG Jan Arentsz, Alkmaar) and started studying Human Movement Sciences at the VU University in Amsterdam. In 2002, he graduated with a specialization in Ergonomics. Since 2002 he is working at TNO (Netherlands Organisation for Applied Scientific Research), where he is involved in applied research and consultancy projects in close cooperation with industrial partners.

In 2005, he started with a PhD-project aimed at muscle fatigue detection during low-intensity occupational work. The project was financed by TNO, Body@Work, the Research Institute MOVE and the Centre for Musculoskeletal Research.

In 2007 he joined the editorial board of the Dutch Journal of Ergonomics and in 2010 he became a member of the committee for ergonomic standards on physical load of the Dutch Organization for Standards (NEN). His current position is researcher and project leader at TNO in Hoofddorp.

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Body@Work - Research Center on Physical Activity, Work and Health

Body@Work is a joint initiative of TNO Quality of Life, Leiden, The Netherlands and VU University, and VU University Medical Centre, Amsterdam, The Netherlands. This research center focuses on the research topics "work and health" and "lifestyle, health and sports". For these topics, Body@Work provides state of the art knowledge for fellow researchers and policymakers of governmental and commercial institutes.

www.bodyatwork.nl

Improve to MOVE

VU University Research Institute MOVE is a collaboration between researchers of the Faculty of Human Movement Sciences, VU University Medical Center and the Academic Centre for Dentistry Amsterdam. The research of MOVE is related to human movement and health, with an emphasis on prevention and recovery of injury and disorders of the (neuro-)musculoskeletal system and on optimal recovery of tissue and function. MOVE aims at fundamental, multidisciplinary and translational research, especially in the fields of (oral) regenerative medicine, rehabilitation and sports.

www.move.vu.nl

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