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Fatigue in assembly work: a contribution to understand the state of fatigue in real work conditions

Thesis submitted to the Faculty of Engineering in fulfillment of the requirements for the degree of Doctor of Philosophy in Occupational Safety and Health

by

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Fatigue in assembly work: a contribution to understand the state of fatigue in real work conditions

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MUITO OBRIGADA

ABSTRACT

Repetitive manual work is a contributing factor to the development of work-related upper limb disorders (WRULDs). Work requirements such as work duration, lack of physical variation and workstation design can increase the risk of muscle fatigue and, consequently, the development of WRULDs. There are still numerous gaps knowledge concerning the influence of these factors on musculoskeletal health during repetitive tasks involving the manual handling of low loads at high frequency such as assembly, particularly in real work conditions.

This thesis aimed to develop a cross-cultural adaptation of an instrument to measure work-related perceived fatigue for the Portuguese language and study the reliability and validity of the data gathered with this instrument; determine the effects of work duration on electromyographic (EMG) manifestation of muscle fatigue and on perceived fatigue; determine the effects of job rotation on EMG manifestation of muscle fatigue and on position sense acuity of the wrist; and assess the ability of an inertial motion capture system to quantify upper-limb mechanical exposure between two assembly lines with different mechanization levels in realistic conditions.

To achieve these objectives, a literature review regarding the influence of the task design on the muscle fatigue in low-load repetitive work was conducted. In order to analyze the psychometric proprieties of the Portuguese version of Swedish Occupational Fatigue Inventory (SOFI), a cross-sectional study involving workers of an automotive components industry was carried out. The convergent and discriminant validity, internal consistency reliability and confirmatory factor analysis were performed. Additionally, three field studies were conducted in assembly lines of an automotive components industry. Objective and subjective manifestations of fatigue were obtained via surface EMG of the forearm muscles during low-load contraction and ratings of perceived fatigue, respectively. Wrist position sense errors were assessed by electrogoniometry. A full body inertial motion capture was tested during assembly tasks.

The analysis of scientific literature (Chapter III) suggested that no consistent results were found related to the effects of job rotation and introduction of breaks on muscle activity and perceived discomfort. In addition, few studies were conducted in real occupational settings. The cultural adaptation, validity and reliability process of SOFI into Portuguese language (Chapter IV) revealed that this instrument is a valid and reliable tool to measure industrial work related fatigue. The studies that investigated the influence of working hours and job rotation (Chapter V and VI, respectively) on localized muscle fatigue revealed that these work organization factors did not significantly affect EMG fatigue indexes. However, perceived fatigue significantly increased throughout working time. These results emphasize the importance of compensation strategies used by workers and the difficulty to implement a job rotation system in tasks with high functional similarity. Regarding the ability of the full-body inertial measurement system (Chapter VII) to quantify upper limb mechanical exposure, its use under realistic conditions seems to have some restrictions caused by the influence of electromagnetic interferences.

In conclusion, despite the risk of wrist muscle fatigue during assembly tasks, the EMG manifestations of fatigue were limited. Therefore, these findings support the need to improve the quantification systems of physical exposure in situ.

Keywords: muscle fatigue, forearm muscles, perceived fatigue, electromyography, assembly work.

RESUMO

As tarefas repetitivas contribuem para o desenvolvimento de lesões músculo-esqueléticas dos membros superiores relacionadas com o trabalho (LMEMSRT). As exigências do trabalho, tais como a duração e a ausência de variação da carga de trabalho, bem como o *design* dos postos de trabalho podem aumentar o risco de fadiga muscular e, consequentemente, contribuir para as LMEMSRT. Existem ainda inúmeras lacunas no conhecimento relativamente à influência destes fatores na saúde músculo-esquelética durante tarefas repetitivas que envolvem a movimentação manual de cargas leves a alta frequência como o trabalho de montagem, particularmente em condições reais de trabalho.

Esta tese teve como objetivos traduzir e realizar a adaptação cultural para a língua portuguesa de um instrumento para avaliação da fadiga percebida relacionada com o trabalho e, estudar a confiabilidade e validade dos dados recolhidos por este instrumento; determinar os efeitos do tempo de trabalho na fadiga muscular dos músculos do antebraço e na fadiga percebida através da análise de sinal electromiográfico e escalas de perceção de fadiga, respetivamente; determinar os efeitos da rotação de tarefas na fadiga muscular dos músculos do antebraço e na sensação de posição articular do punho através do sinal electromiográfico e eletrogoniometria, respetivamente; e, por fim, avaliar o desempenho de um sistema inercial de captura de movimento para quantificar a exposição mecânica do membro superior entre duas linhas de montagem com diferentes níveis de automatização, em contexto real de trabalho.

Para atingir os objetivos definidos, foi realizada uma revisão da literatura sobre a influência do *design* da tarefa na fadiga muscular em tarefas repetitivas de baixa carga. Com o intuito de analisar as propriedades psicométricas da versão Portuguesa do *Swedish Occupational Fatigue Inventory* (SOFI) foi desenvolvido um estudo transversal que envolveu a aplicação deste questionário a trabalhadores da indústria de componentes para automóveis. Realizou-se a análise fatorial confirmatória para verificar o ajustamento do modelo e estimou-se a validade convergente e discriminante, assim como a consistência interna. Além disso, foram realizados três estudos de campo em linhas de montagem de uma indústria de componentes para automóveis. As manifestações objetivas e subjetivas de fadiga foram avaliadas através da análise do sinal electromiográfico (EMG) de superfície durante testes de contração e através de escalas de perceção de fadiga, respetivamente. Os erros angulares obtidos na avaliação da sensação de posição articular do punho foram medidos por eletrogoniometria. Foi ainda testado um sistema inercial de captura de movimento durante tarefas de montagem.

A análise do estado da arte (Capítulo III) sugere que não foram encontrados resultados consistentes relativamente aos efeitos da rotação de postos de trabalho, ritmo de trabalho e introdução de pausas, no que concerne à atividade muscular e desconforto percebido pelos trabalhadores. Por outro lado, poucos estudos foram realizados em condições reais de trabalho. O processo de adaptação cultural do SOFI para a língua portuguesa (Capítulo IV), validade e confiabilidade revelou que este instrumento é uma medida válida e confiável para a avaliação da fadiga relacionada com o trabalho industrial. Os estudos que investigaram a influência do horário de trabalho e rotação de postos de trabalho (Capítulo V e VI, respetivamente), na fadiga muscular localizada, revelaram que estes fatores da organização do trabalho não afetam significativamente os indicadores de fadiga analisada através do sinal EMG. No entanto, a fadiga percebida pelos trabalhadores aumentou significativamente com o tempo de trabalho. Estes resultados enfatizam a importância das estratégias de compensação utilizadas pelos trabalhadores e a dificuldade de implementar um sistema de rotação de postos de trabalho em tarefas com similaridade funcional. No que diz respeito ao desempenho do sistema inercial de captura do movimento (Capítulo VII), para quantificar a exposição mecânica do membro superior, verificou-se que a sua utilização em condições reais apresenta algumas limitações relacionadas com interferências eletromagnéticas.

Em conclusão, apesar do risco de fadiga muscular dos músculos do antebraço durante a realização de tarefas de montagem, as manifestações de fadiga muscular obtidas através da análise do sinal eletromiográfico foram limitadas. Estes resultados confirmam assim a necessidade de serem melhorados os sistemas usados na quantificação da exposição *in situ.*

Palavras-chave: fadiga muscular, músculos do antebraço, fadiga percebida, eletromiografia, trabalho de montagem.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AD	anterior deltoid
ANOVA	analysis of variance
APA	American psychological association
APDF	amplitude probability distribution function
ARV	average rectified value
AVE	average variance extracted
BC	biceps brachii
BIA	bioelectric impedance analysis
BMI	body mass index
CFA	confirmatory factor analysis
CFI	confirmatory fit index
GFI	goodness of fit index
CR	composite reliability
CTS	carpal tunnel syndrome
CV	conduction velocity
DSI	Dimitrov spectral index
ECR	extensor carpi radialis muscle
ECRB	extensor carpi radialis brevis
ECRL	extensor carpi radialis longus
ECU	extensor carpi ulnaris
EMG	electromyography
EODS	European occupational disease statistics
ER	extensor carpi radialis longus
EVA	exposure variation analysis
FCR	flexor carpi radialis
FCU	flexor carpi ulnaris
FFT	fast Fourier transform
FR	flexor carpi radialis
iEMG	integrated amplitude
LFF	low-frequency fatigue
LMEMSRT	lesões músculo-esqueléticas dos membros superiores relacionadas com o trabalho
LPS	lean production system
MAV	mean absolute value
MF	median frequency

mEMG	windowed amplitude
MES	myoelectric signal
MF_{init}	initial median frequency
MF_{slope}	median frequency slope
MI	modification indices
MNF	mean frequency
MPF	mean power frequency
MSDs	musculoskeletal disorders
MTM	methods-time measurement
MU	motor units
MUAP	motor unit action potential
MVC	maximum voluntary contraction
MVE	maximum voluntary electrical activity
NMF_{slope}	normalized regression coefficient of the median frequencies
NUMMI	New United Motor Manufacturing, Inc.
PGFI	parsimony goodness-of-fit index
RMS	root-mean-square
RMSEA	root mean square error of approximation
RPD	rating of perceived discomfort
RPE	rating of perceived exertion
RVE	sub-maximal reference contraction
SOFI	Swedish occupational fatigue inventory
TC	triceps brachii
TLI	Tucker Lewis index
TPS	Toyota Production System
UT	upper trapezius
VAS	visual analogue scale
WPM	words per minute
WRMSDs	work-related musculoskeletal disorders
WRULDs	work-related upper limb disorders
ZCR	zero-crossing rate

LIST OF PUBLICATIONS

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Santos, J., Carvalhais, C., Costa, A., Abreu, A. B., & Silva, M. V. (2014). Effect of an exercise program on musculoskeletal symptoms and productivity: An ongoing study in an automotive industry. In M. Vieira da Silva, R. Oliveira, M. Rodrigues, M. Nunes, J. Santos, C. Carvalhais, … A. Xavier (Eds.), *3rd International Congress on Environmental Health: Proceedings Book* (pp. 217-219). Porto, Portugal: Scientific Area of Environmental Health of Allied Health Sciences School of Polytechnic Institute of Porto.

CHAPTER 1: Introduction

1.1. General introduction

The exposure to physical risk factors such awkward positions and repetitive hand or arm movements in the workplaces has been increasing since 1991 and it has been associated with pain episodes and fatigue, deteriorated posture and/or altered movement coordination, which can lead to musculoskeletal disorders (MSDs) (Da Costa & Vieira, 2010; Eurofound, 2012; Nordander et al., 2009; Thomsen et al., 2007). In Europe, the exposure to repetitive hand or arm movements and tiring or painful positions are the most prevalent physical risks at work. Indeed, 63% of European workers have reported to carry out repetitive hand or arm movements and 46% to endure tiring or painful positions for at least a quarter of the time (Eurofound, 2012). The European Occupational Disease Statistics (EODS) reported that, in 2005, upper-limb musculoskeletal disorders such as epicondylitis of the elbow, tenosynovitis of the hand or wrist and a neurological disease of the wrist, the carpal tunnel syndrome (CTS), are the most frequent disorders in the 12 Member States (EU-OSHA, 2010). However, work-related musculoskeletal disorders (WMSDs) are a complex condition influenced not only by the mentioned physical risk factors, but also by environmental (e.g. temperature) (Magnavita, Elovainio, de Nardis, Heponiemi, & Bergamaschi, 2011), psychosocial (e.g., job demands) (Bongers, Kremer, ter Laak, & Bongers, 2002), organizational (e.g., design of individual jobs) (Wells, Mathiassen, Medbo, & Winkel, 2007) and individual factors (e.g. gender, body mass) (Cole & Rivilis, 2004; Nordander et al., 2008; Wearing, Hennig, Byrne, Steele, & Hills, 2006) that interact and, consequently, increase the risk of injury.

Numerous studies reported that disorders in wrist and hands are associated with repetitive manual work (Barr, Barbe, & Clark, 2004; Hansson et al., 2000; Muggleton, Allen, & Chappell, 1999; Rempel, 1995). A cross-sectional study carried out by Thomsen, Hansson, Mikkelsen, & Lauritzen (2002), found a relation between exposure of highly repetitive, non-forceful work and an increased risk of CTS. Bonfiglioli et al. (2007) investigated female workers exposure to the same levels of repetitiveness and hand force but to a different weekly duration of exposure (full-time *vs* part-time cashiers). The results demonstrated that full-time workers with an inadequate recovery time had an increased risk of CTS. A prospective surveillance study conducted in France focused on finding the risk factors related to work organization for incident CTS, revealed that payment on a piecework basis and work pace dependent on automatic rate were associated with this disorder (Petit et al., 2015). Additionally, a literature review conducted by Treaster & Burr (2004) suggest that women are significantly more affected by upper extremity musculoskeletal disorders than men. A more recent study showed that females had a significantly higher risk of musculoskeletal disorders as well as less time for recovery than men (Nordander et al., 2008). Thus, it is important to study the potential risk factors, as time-related aspects of exposure, for development of disorders in the wrists and hands in hand-intensive work.

Manual assembly work is an example of a repetitive task involving the manual handling of low loads at high frequency. Assembly processes are characterized by standardized procedures, cycle times less than 30 s, high repetitiveness of movements and low variability (Kilbom, 1994; Wells et al., 2007). In these production systems, individual workstations are arranged in assembly line or assembly cell in order to improve productivity. Assembly work is frequently used in the automotive industry (Landau et al., 2008). Some automotive assembly tasks require muscle contraction at low-moderate effort levels, namely in the automotive components industry (e.g. assemble mechanical cables) (see Figure 1). In Portugal, auto components industry is an important cluster of manufacturing, aggregating about 200 companies and creating approximately 41 000 direct jobs (AFIA, 2015). This industry emerged in the 1960s with the first assembly lines. Renault and AutoEuropa projected in the 1980s and 1990s have increased production at an European scale. In 1986, Portugal entry into the European Union allowed the development of this industry (Féria, 1999). Currently it exports more than 80 percent of the production by providing components for automobile models manufactured in Europe (AFIA, 2015).

Over the last years, the automotive assembly systems were subjected to great transformations due to technological advancements, product quality requirements and the need to reduce production time and costs. These changes lead to new forms of work organization and management practices focused on the characteristics and prevalence of high performance work systems – work intensification (Green, 2004). According to Green & McIntosh (2001) work intensification is partially related to changing in work organization. The principles of Taylorism dominated the production management in the early 20th century. In 1984, the Lean Production was officially introduced in the United States, when the New United Motor Manufacturing, Inc. (NUMMI) was established as a joint venture between Toyota and General Motors (Shah

& Ward, 2007). However, this system emerged earlier with the first oil crisis in 1973 and had its origin in Toyotist or Japanese-style organizational model, known as the Toyota Production System (TPS) (Holweg, 2007). Portugal in the EU15 has an overrepresentation of lean production and Taylorist forms (Eurofound, 2009).

Figure 1. Workstations in the auto components assembly lines.

Lean practices have become widely adopted in manufacturing, but the results of research on the implementation of the principles of lean management and its effects on musculoskeletal health differ between studies (Arezes, Dinis-Carvalho, & Alves, 2010). Lean Production is characterized by short-cyclic tasks and rationalization strategies, often associated with flow structures such as assembly lines (Johansson & Abrahamsson, 2009), which can lead to intensification of work and, consequently, increase the risk of WMSDs (Wells et al., 2007). However, a study carried out by Womack, Armstrong, & Liker (2009) in an automobile manufacturing plant, suggest that lean manufacturing does not necessarily increase workers' WMSDs risk, if the lean production principles are properly implemented.

A recent systematic review developed by Westgaard & Winkel (2011), examined scientific papers and official European Union documents that investigated the effects of production systems rationalization and organizational-level measures on musculoskeletal and mental health as well as related risk factors. In general, this review revealed that lean practices studies report a negative outcome for health and risk factors. Though, level and time of implementation are identified as determining factors for the consequences of this rationalization strategy. Figure 2 shows a simple conceptual model that illustrates the relation between rationalization and worker health effects. According to this model, social concepts of rationalization as determined by market conditions, regulation, technological prerequisites and other constraints as well as organization strategy (include production system design decisions) influence risk factors and musculoskeletal and mental health. The term “system modifiers” introduced in the model, refers to actions that in a rationalization process (e.g. lean production) can influence mechanical exposure and, consequently, health outcome. Individual-related factors such as gender and age designated as “individual modifiers” may also influence the relation between rationalization and health.

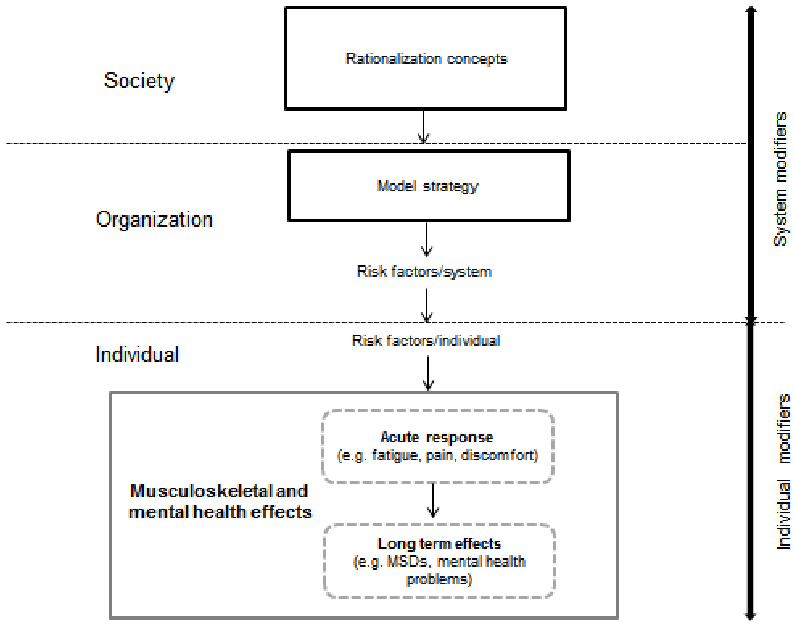


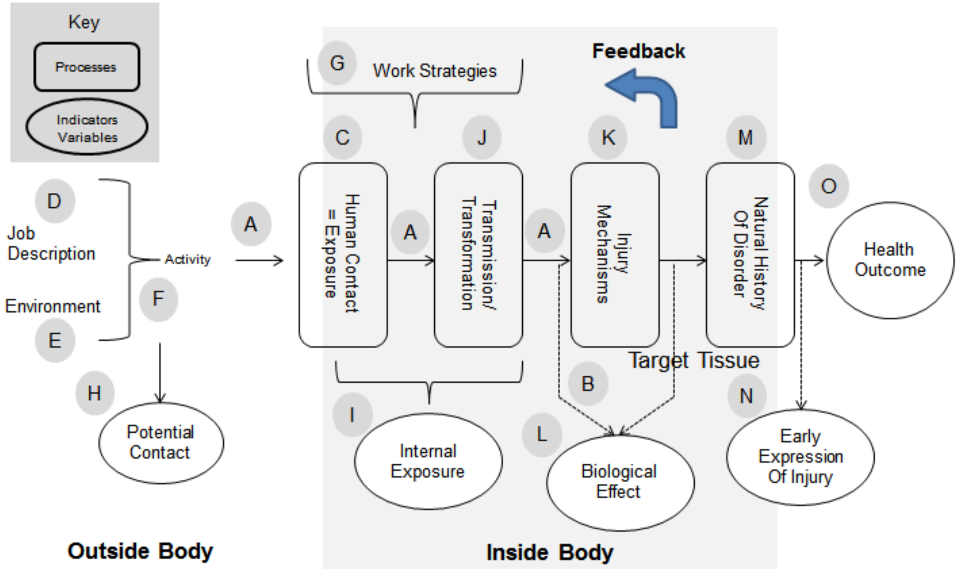
Figure 2. A conceptual model of the relation between rationalization concepts and worker musculoskeletal and mental health effects adapted from Westgaard & Winkel (2011). This model was revised by Westgaard & Winkel (2011) and represent a further development of previously published models (Neumann, Ekman, & Winkel, 2009; Westgaard & Winkel, 1997; Winkel & Westgaard, 1992).

Rationalization involves changes in work organization. Work organization is a broad concept influenced by the choices of the organization regarding the structure of the production process, relationship between staff and production departments, responsibility and involvement of employees as well as the design of individual jobs (Eurofound, 2009). Sauter et al. (2002) use the expression “organization of work” that refers to the work process and to the organizational practices that influence job design. Additionally, this concept includes external factors, such as economic and legal framework and technological advancements.

This contemporary trend to production system rationalization with the purpose to ensure a “sustainable production system” has influenced time aspects of biomechanical exposure, such as frequency and duration (Winkel & Westgaard, 2008). Some ergonomic interventions (e.g., reduced non-neutral postures) aim to reduce other exposure factor – amplitude. However, these interventions can influence time-related variables, reducing variation and increasing duration of exposure. Biomechanical exposure include three dimensions – amplitude, frequency (or time variation pattern) and duration (Winkel & Mathiassen, 1994; Winkel & Westgaard, 1992). Considering these dimensions and based on the exposure concepts presented by Lioy (1999) and Zartarian, Ott, & Duan (1997); Wells, Van Eerd, & Hägg (2004), proposed a mechanical exposure model for use in musculoskeletal epidemiology and ergonomic risk assessment, as shown in Figure 3.

In this model, force is the key agent responsible for the development of musculoskeletal disorders. In general, “outside the body” corresponds to “external exposure”. Work organization schemes and workplace design are examples of external exposure. Feedback presented in Figure 3 can be given by target tissues through initiators factors such as fatigue, pain or discomfort.

Time aspects of work have particularly interest in the current time-intensive production systems with strictly standardized assembly procedures at time-balanced station on the assembly-line. However, ergonomists and engineers have different perspectives about time aspects of work in manufacturing environments. The lack of quantitative assessment tools related to time in the ergonomic field difficult the inclusion of ergonomic principles during the design of workstations and tasks in the production planning phase (Wells et al., 2007). In order to support the research related to the assessment of aspects of physical variation in workplaces, Mathiassen (2006) proposed two distinct concepts: variation defined as ‘‘the change in exposure across time’’, and diversity meaning ‘‘the extent that exposure entities differ’’. Job rotation is an administrative control used to increase physical variation (Möller, Mathiassen, Franzon, & Kihlberg, 2004; Wells, McFall, & Dickerson, 2010). However, interventional and epidemiological studies do not consistently support the effectiveness of job rotation against musculoskeletal disorders (Jorgensen, Davis, Kotowski, Aedla, & Dunning, 2005; Mathiassen, 2006; Wells et al., 2007), as well as muscle fatigue. Given the ineffectiveness of this strategy to increase physical variation, other intervention focused in changing the way the operator performs the task – motor variability – has emerged (Srinivasan & Mathiassen, 2012).



Legend: A – Agent; B – Target tissue; C – Exposure (human contact); D – Job description; E – Environment (description); F – Activity; G – Work strategies; H – Potential contact; I – Internal exposure; J – Transmission and transformation; K – Injury mechanism (s); L – Biological effect; M – Natural history of disorder; N – Early expression of disorder; O – Health outcome

Figure 3. Mechanical exposure model proposed by Wells et al. (2004).

The scientific literature considers that musculoskeletal risk arises from several contributing factors present in the work environment. Production system design affects temporal pattern of the workload as work-rest schemes, work pace, working day and physical variation of tasks (Wells et al., 2007). In addition, these factors can also influence work strategies in the workplace which in turn affect the level of estimated physical exposures. Thus, it is recognized that quantification of physical exposure (e.g. muscle activity, joint kinematic and kinetics) in real working conditions is required (Marras, Cutlip, Burt, & Waters, 2009).

The exposure to repetitive low force contractions (muscle activity levels between 5 to 20 percent of the maximum capacity) for extended periods of time without sufficient recovery may lead to acute physiological responses, such as muscle fatigue (Blangsted, Sjøgaard, Madeleine, Olsen, & Søgaard, 2005; Søgaard, Blangsted, Jørgensen, Madeleine, & Sjøgaard, 2003). Therefore, muscle fatigue may provide a biomarker for cumulative exposure to repetitive tasks and its measurement can help to prevent the development of WMSDs (Dennerlein, Ciriello, Kerin, & Johnson, 2003; Madeleine, 2010).

Several authors defined muscle fatigue as an exercise-induced reduction in the maximal capacity to generate force or power output whether or not the task can be sustained (Bigland-Ritchie & Woods, 1984; Enoka & Duchateau, 2008; Søgaard, Gandevia, Todd, Petersen, & Taylor, 2006; Vøllestad, 1997). According to other authors, muscle fatigue can occur as a result of changes in voluntary drive (central nervous systems and/or neuromuscular junction) - central fatigue – and/or the muscle properties - peripheral fatigue (Gandevia, Allen, & McKenzie, 1995; Gandevia, Enoka, McComas, Stuart, & Thomas, 1995; Gandevia, 2001; Willliams & Ratel, 2009). Luttmann, Jäger, & Laurig (2000) referred that this phenomenon is usually defined in the ergonomics context as the reduction in the force generation capacity of a muscle during the course of the work. According to Blangsted et al. (2005), biochemical and physiological changes which occur during low-force tasks are able to affect the contractile capability of the muscle. It is hypothesized that during low-force and long-term contractions, a homogenous activation of the same single muscle fibers occurs which can lead to degenerative changes in the muscles (Sjøgaard, Lundberg, & Kadefors, 2000).

The schematic diagram presented in Figure 4 was proposed by De Luca (1992) and integrates the known factors that directly affect the shape of the motor unit action potential (MUAP) during a sustained contraction above 30% maximum voluntary contraction (MVC). The accumulation of intracellular lactate and hydrogen ions in the muscle fibers is suggested to be the major cause of muscle fatigue. This process leads to a decrease in muscle fiber conduction velocity (CV), which changes the shape of the MUAP waveform and, hence, results in a spectral modification of the surface electromyography (EMG) signal.

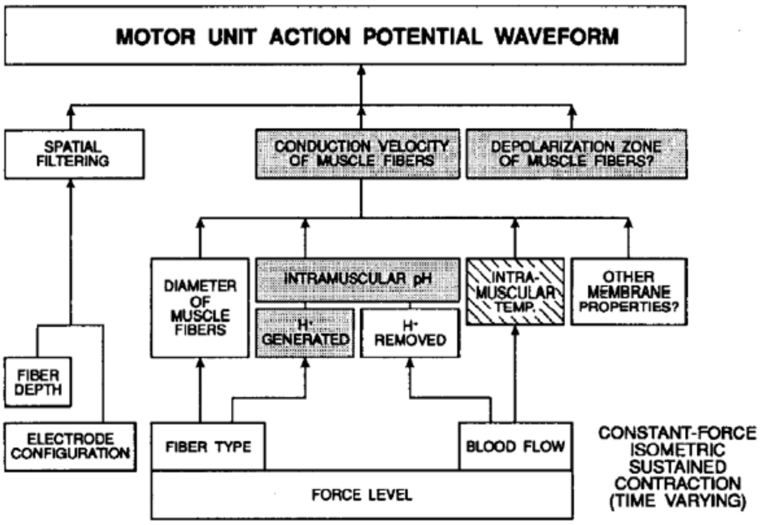


Figure 4. Factors which affect the shape of the motor unit action potential during a sustained contraction. Factors that are modified as function of time during a sustained constant-force isometric contraction above 30% MVC are indicated in shaded boxes De Luca (1992).

EMG is one of several methods used to detect the occurrence and development of muscle fatigue (De Luca, 1997), during both sustained isometric as well as dynamic contractions. Cifrek, Medved, Tonković, & Ostojić (2009) enumerated the main advantages of the application of EMG method which are: non-invasive method, easy to apply in workplace (*in situ*); real-time muscle fatigue monitoring during a work task; ability to monitor fatigue of a specific muscle; and correlation with biochemical and physiological changes in muscles that occurred during a fatigue process. Surface EMG is a useful tool in the ergonomics field, allowing the evaluation of work performance (Soderberg, 1992). Despite others EMG amplitude indicators described in the literature (e.g. zero-crossing rate (ZCR)), there are two indicators in the time domain commonly used in fatigue studies in ergonomics: average rectified value (ARV) (or mean absolute value (MAV)) and root-mean-square (RMS). These indicators are not generally used alone to describe muscle fatigue phenomena. Mean frequency (MNF) and median frequency (MF) are the spectral parameters most widely applied as EMG fatigue indexes. De Luca (1997) referred that MF is a preferable fatigue index, though MNF can also be used. MF is less sensitive to noise, less sensitive to signal aliasing and more sensitive to the biochemical and physiological processes that occur within the muscles during sustained contractions (De Luca, 1984; Merletti, Knaflitz, & De Luca, 1992). Figure 5 shows the MF modification that occurs in the EMG signal during sustained contractions. Manifestations of muscle fatigue are usually characterized by a decrease in the frequency content (MNF and MF) accompanied by an increase in amplitude of the

EMG signal (RMS) (Basmajian & De Luca, 1985; De Luca, 1984; Kallenberg, Schulte, Disselhorst-Klug, & Hermens, 2007). The decrease of spectral descriptors reflects a decrease of muscle fiber conduction velocity, changes in firing rates and time synchronous in the activity of particular motor units (MU) (Cifrek et al., 2009; Hägg, 1992). On the other hand, the increase in EMG amplitude as a function of time during sustained fatiguing submaximal contractions is generally attributed to the recruitment of additional MU in order to compensate the loss of contractility of fatigued MU (Maton, 1981; Moritani, Muro, & Nagata, 1986; Moritani, Stegeman, & Merletti, 2004). Temporal behavior of EMG parameters can be analyzed by regression analysis, particularly during sustained isometric contractions at load levels below approximately 20% of MVC (Hägg, Luttmann, & Jäger, 2000; Merletti, Lo Conte, & Orizio, 1991; Moritani et al., 2004).

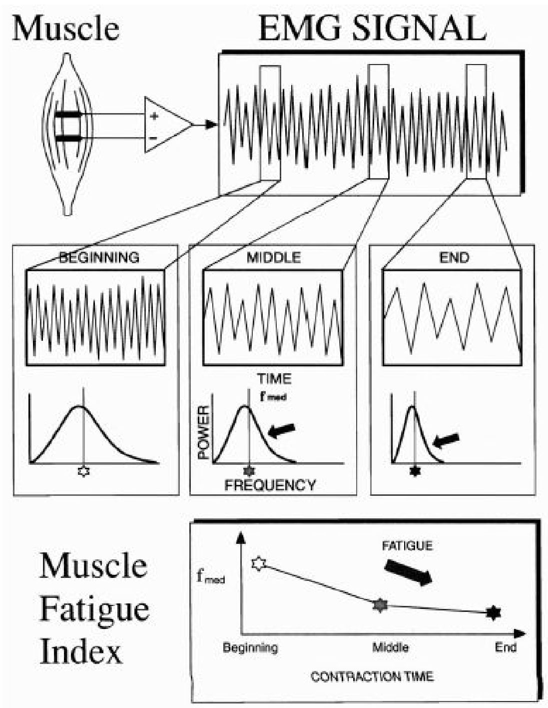


Figure 5. Scheme of the spectral modification that occurs in the EMG signal during sustained contractions (from De Luca, 1997).

To ensure an adequate EMG evaluation of fatigue in an occupational context, it is essential that EMG parameters be evaluated at specific time under the same conditions. Thus, two methods can be applied: 1) execution of test contractions performed before, during and after work with a known force in a defined posture, and 2) selection of specific working periods with similar biomechanical load of the muscle under test (Gazzoni, 2010; Hägg et al., 2000). However, during dynamic conditions the EMG is no stationary and some confounding factors related to movement of muscle under the electrodes may increase the complexity of the interpretation of EMG signals. Factors such as modifications in force output, muscle length, position and distance of electrodes, as well as characteristics of task dynamics (e.g. movement velocity) are difficult to control during working activities (Farina, 2006; Madeleine, Bajaj, Søgaard, & Arendt-Nielsen, 2001).

Fatigue studies in ergonomics intend to improve the quality of work, as for example limiting the time of tasks capable of inducing muscle fatigue. Muscle activity and fatigue are included on the dimensions of human performance and can also provide an indication about the adequacy of temporal organization of work (such as duration, work pace, rest breaks patterns) (Dempsey, Mathiassen, Jackson, & O'Brien, 2010). Bosch, de Looze, & van Dieën (2007) showed EMG manifestations of muscle fatigue of trapezius muscles during normal (8-hours) and extended (9.5-hours) working days of light manual work (5-15% MVC). The results of this field study also revealed no clear relation between perceived discomfort and objective indicators of fatigue. A laboratory study carried out by Björklund, Crenshaw, Djupsjöbacka, & Johansson (2000) investigated the effect of a repetitive low intensity task to fatigue on shoulder position sense. The application of the experimental protocol demonstrated a significant reduction of shoulder proprioceptive acuity. Considering the importance of forearm muscles during repetitive manual work, Bennie, Ciriello, Johnson, & Dennerlein (2002) and Dennerlein et al. (2003) simulated 8h-hours working day and, using EMG measurements and electrostimulation investigated the progress of muscle fatigue in extensor carpi ulnaris. Both studies showed an increase of muscle fatigue over the course of working day without perceived discomfort by the participants. Other studies involving isometric handgrip exercises at low load level resulted in low-frequency fatigue (LFF) of forearm muscles (Byström & Fransson-Hall, 1994; Byström & Kilbom, 1991).

There are only few studies related to the development of muscle fatigue during realistic working tasks, most likely due to the acyclic nature of the performed tasks, to the constraints associated with the production goals, and even to the characteristics of the sample (e.g. Body mass index (BMI), work experience, age, among others).

Additionally, to our knowledge there are no studies about the influence of exposure to repetitive manual task on wrist position sense in a real-occupational setting.

The use of surface EMG in ergonomics can be quite valuable to continuous monitoring of local muscle fatigue during performance of different types of working tasks. However, the state of “fatigue” is multidimensional and it can be described considering five dimensions: lack of energy, physical exertion, physical discomfort, lack of motivation and sleepiness (Åhsberg, 2000). Several studies of occupational fatigue have used subjective ratings and physiological methods of measurement (Bosch et al., 2007; Keir, Sanei, & Holmes, 2011; Kimura, Sato, Ochi, Hosoya, & Sadoyama, 2007; Mathiassen & Winkel, 1996; Seghers, Jochem, & Spaepen, 2003). Self-administered questionnaires are important to assess perceived fatigue related to work, and the use of reliable and valid instruments, is essential. Among other advantages, the cross-cultural adaptation of an instrument previously developed and validated in another language allows comparisons between national/cultural groups relying on a standard measure designed and adapted to measure the phenomenon cross-culturally and it is less costly and time-consuming than generating a new measure (Guillemin, Bombardier, & Beaton, 1993). The process of cross-cultural adaptation intend to ensure a consistency in the content and face validity between original and target versions of a questionnaire (Beaton, Bombardier, Guillemin, & Ferraz, 2000; Wild et al., 2005). The Swedish Occupational Fatigue Inventory (SOFI) developed by (Åhsberg, 2000) is a self-report instrument that has been originally created to measure work-related perceived fatigue (Åhsberg, 2000; Åhsberg & Gamberale, 1998). In Portugal, there is not any validated measure of fatigue that is specifically designed for workers perception.

1.2. References

AFIA. (2015). Indústrias de componentes para automóveis - Estatísticas 2014. Retrieved May 8, 2015, from http://www.afia.pt/index.php?option=com_content&task=view&id=28&Itemid=42&lang=pt_PT

Åhsberg, E. (2000). Dimensions of fatigue in different working populations. *Scandinavian Journal of Psychology*, *41*(3), 231–241.

Åhsberg, E., & Gamberale, F. (1998). Perceived fatigue during physical work: An experimental evaluation of a fatigue inventory. *International Journal of Industrial Ergonomics*, *21*(2), 117–131.

Arezes, P. M., Dinis-Carvalho, J., & Alves, A. C. (2010). Threats and Opportunities for Workplace Ergonomics in Lean Environments. In *17th International Annual EurOMA Conference -Managing Operations in Service Economics* (p. 10).

Barr, A. E., Barbe, M. F., & Clark, B. D. (2004). Work-related musculoskeletal disorders of the hand and wrist: epidemiology, pathophysiology, and sensorimotor changes. *The Journal of Orthopaedic and Sports Physical Therapy*, *34*(10), 610–627.

Basmajian, J. V, & De Luca, C. J. (1985). *Muscles Alive: Their Functions Revealed by Electromyography* (5th ed.). Easton, Maryland: Williams & Wilkins.

Beaton, D. E., Bombardier, C., Guillemin, F., & Ferraz, M. B. (2000). Guidelines for the Process of Cross-Cultural Adaptation of Self-Report Measures. *Spine*, *25*(24), 3186-3191.

Bennie, K. J., Ciriello, V. M., Johnson, P. W., & Dennerlein, J. T. (2002). Electromyographic activity of the human extensor carpi ulnaris muscle changes with exposure to repetitive ulnar deviation. *European Journal of Applied Physiology*, *88*(1-2), 5–12.

Bigland-Ritchie, B., & Woods, J. J. (1984). Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle & Nerve*, *7*(9), 691–699.

Björklund, M., Crenshaw, A. G., Djupsjöbacka, M., & Johansson, H. (2000). *Position sense acuity is diminished following repetitive low-intensity work to fatigue in a simulated occupational setting. European journal of applied physiology*, *81*(5), 361-370.

Blangsted, A. K., Sjøgaard, G., Madeleine, P., Olsen, H. B., & Søgaard, K. (2005). Voluntary low-force contraction elicits prolonged low-frequency fatigue and changes in surface electromyography and mechanomyography. *Journal of Electromyography and Kinesiology*, *15*(2), 138–148.

Bonfiglioli, R., Mattioli, S., Fiorentini, C., Graziosi, F., Curti, S., & Violante, F. S. (2007). Relationship between repetitive work and the prevalence of carpal tunnel syndrome in part-time and full-time female supermarket cashiers: A quasi-experimental study. *International Archives of Occupational and Environmental Health*, *80*(3), 248–253.

Bongers, P. M., Kremer, A. M. & ter Laak, J. (2002). Are psychosocial factors, risk factors for symptoms and signs of the shoulder, elbow, or hand/wrist?: A review of the epidemiological literature. *American Journal of Industrial Medicine*, *41*(5), 315–342.

Bosch, T., de Looze, M. P., & van Dieën, J. H. (2007). Development of fatigue and discomfort in the upper trapezius muscle during light manual work. *Ergonomics*, *50*(2), 161–177.

Byström, S., & Fransson-Hall, C. (1994). Acceptability of intermittent handgrip contractions based on physiological response. *Human Factors*, *36*(1), 158–171.

Byström, S., & Kilbom, A. (1991). Electrical stimulation of human forearm extensor muscles as an indicator of handgrip fatigue and recovery. *European Journal of Applied Physiology and Occupational Physiology*, *62*(5), 363–368.

Cifrek, M., Medved, V., Tonković, S., & Ostojić, S. (2009). Surface EMG based muscle fatigue evaluation in biomechanics. *Clinical Biomechanics*, *24*(4), 327-340.

Cole, D. C., & Rivilis, I. (2004). Individual factors and musculoskeletal disorders: A framework for their consideration. *Journal of Electromyography and Kinesiology*, *14*(1), 121-127.

Da Costa, B. R., & Vieira, E. R. (2010). Risk factors for work-related musculoskeletal disorders: A systematic review of recent longitudinal studies. *American Journal of Industrial Medicine*, *53*(3), 285-323.

De Luca, C. J. (1984). Myoelectrical manifestations of localized muscular fatigue in humans. *Critical Reviews in Biomedical Engineering*, *11*(4), 251–279.

De Luca, C. J. (1992). Spectral compression of the EMG signal as an index of muscle fatigue. In A. J. Sargeant & D. Kernell (Eds.), *Neuromuscular Fatigue* (pp. 44–51). Amsterdam, The Netherlands: Royal Netherlands Academy of Arts and Sciences.

De Luca, C. J. (1997). The use of surface electromyography in biomechanics. In *Journal of Applied Biomechanics*, *13*(2), 135–163.

Dempsey, P. G., Mathiassen, S. E., Jackson, J. A., & O'Brien, N. V. (2010). Influence of three principles of pacing on the temporal organisation of work during cyclic assembly and disassembly tasks. *Ergonomics*, *53*(11), 1347–1358.

Dennerlein, J. T., Ciriello, V. M., Kerin, K. J., & Johnson, P. W. (2003). Fatigue in the forearm resulting from low-level repetitive ulnar deviation. *AIHA Journal : A Journal for the Science of Occupational and Environmental Health and Safety*, *64*(6), 799–805.

Enoka, R. M., & Duchateau, J. (2008). Muscle fatigue: what, why and how it influences muscle function. *The Journal of Physiology*, *586*(1), 11–23.

EU-OSHA. (2010). *OSH in figures: Work-related musculoskeletal disorders in the EU — Facts and figures*. Luxembourg: Publications Office of the European Union.

Eurofound. (2009). *Working conditions in the European Union: Work organisation*. Luxembourg: Office for Official Publications of the European Communities.

Eurofound. (2012). *Fifth European Working Conditions Survey*. Luxembourg: Publications Office of the European Union.

Farina, D. (2006). Interpretation of the surface electromyogram in dynamic contractions. *Exercise and Sport Sciences Reviews*, *34*(3), 121-127.

Féria, L. P. (1999). *A História do Sector Automóvel em Portugal (1895-1995)*. Lisboa: Gabinete de Estudos e Prospetiva Económica do Ministério da Economia (GEPE).

Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews*, *81*(4), 1725–1789.

Gandevia, S. C., Allen, G. M., & McKenzie, D. K. (1995). Central fatigue. Critical issues, quantification and practical implications. *Advances in Experimental Medicine and Biology*, *384*, 281–294.

Gandevia, S. C., Enoka, R. M., McComas, A. J., Stuart, D. G., & Thomas, C. K. (1995). Neurobiology of muscle fatigue. Advances and issues. *Advances in Experimental Medicine and Biology*, *384*, 515–525.

Gazzoni, M. (2010). Multichannel surface electromyography in ergonomics: Potentialities and limits. *Human Factors and Ergonomics In Manufacturing*, *20*(4), 255–271.

Green, F. (2004). Why has work effort become more intense? *Industrial Relations*, *43*(4), 709–741.

Green, F., & McIntosh, S. (2001). The intensification of work in Europe. *Labour Economics*, *8*(2), 291–308.

Guillemin, F., Bombardier, C., & Beaton, D. (1993). Cross-cultural adaptation of health-related quality of life measures: Literature review and proposed guidelines. *Journal of Clinical Epidemiology*, *46*(12), 1417-1432.

Hägg, G. M. (1992). Interpretation of EMG spectral alterations and alteration indexes at sustained contraction. *Journal of Applied Physiology*, *73*(4), 1211–1217.

Hägg, G. M., Luttmann, A., & Jäger, M. (2000). Methodologies for evaluating electromyographic field data in ergonomics. *Journal of Electromyography and Kinesiology*, *10*(5), 301-312.

Hansson, G. Å., Balogh, I., Ohlsson, K., Pålsson, B., Rylander, L., & Skerfving, S. (2000). Impact of physical exposure on neck and upper limb disorders in female workers. *Applied Ergonomics*, *31*(3), 301–310.

Holweg, M. (2007). The genealogy of lean production. *Journal of Operations Management*, *25*(2), 420–437.

Johansson, J., & Abrahamsson, L. (2009). The good work - A Swedish trade union vision in the shadow of lean production. *Applied Ergonomics*, *40*(4), 775–780.

Jorgensen, M., Davis, K., Kotowski, S., Aedla, P., & Dunning, K. (2005). Characteristics of job rotation in the Midwest US manufacturing sector. *Ergonomics*, *48*(15), 1721–1733.

Kallenberg, L. A. C., Schulte, E., Disselhorst-Klug, C., & Hermens, H. J. (2007). Myoelectric manifestations of fatigue at low contraction levels in subjects with and without chronic pain. *Journal of Electromyography and Kinesiology*, *17*(3), 264–274.

Keir, P. J., Sanei, K., & Holmes, M. W. R. (2011). Task rotation effects on upper extremity and back muscle activity. *Applied Ergonomics*, *42*(6), 814–819.

Kilbom, Å. (1994). Repetitive work of the upper extremity: Part I—Guidelines for the practitioner. *International Journal of Industrial Ergonomics*, *14*(1-2), 51–57.

Kimura, M., Sato, H., Ochi, M., Hosoya, S., & Sadoyama, T. (2007). Electromyogram and perceived fatigue changes in the trapezius muscle during typewriting and recovery. *European Journal of Applied Physiology*, *100*(1), 89–96.

Landau, K., Rademacher, H., Meschke, H., Winter, G., Schaub, K., Grasmueck, M., … Schulze, J. (2008). Musculoskeletal disorders in assembly jobs in the automotive industry with special reference to age management aspects. *International Journal of Industrial Ergonomics*, *38*(7-8), 561–576.

Lioy, P. J. (1999). The 1998 ISEA Wesolowski Award Lecture Exposure analysis: reflections on its growth and aspirations for its future, *Journal of Exposure Analysis and Environmental Epidemiology, 9*(4), 273–281.

Luttmann, A., Jäger, M., & Laurig, W. (2000). Electromyographical indication of muscular fatigue in occupational field studies. *International Journal of Industrial Ergonomics*, *25*(6), 645–660.

Madeleine, P. (2010). On functional motor adaptations: From the quantification of motor strategies to the prevention of musculoskeletal disorders in the neck-shoulder region. *Acta Physiologica*, *199*(Suppl. 679), 1–46.

Madeleine, P., Bajaj, P., Søgaard, K., & Arendt-Nielsen, L. (2001). Mechanomyography and electromyography force relationships during concentric, isometric and eccentric contractions. *Journal of Electromyography and Kinesiology*, *11*(2), 113–121.

Magnavita, N., Elovainio, M., de Nardis, I., Heponiemi, T., & Bergamaschi, A. (2011). Environmental discomfort and musculoskeletal disorders. *Occupational Medicine*, *61*(3), 196–201.

Marras, W. S., Cutlip, R. G., Burt, S. E., & Waters, T. R. (2009). National occupational research agenda (NORA) future directions in occupational musculoskeletal disorder health research. *Applied Ergonomics*, *40*(1), 15-22.

Mathiassen, S. E. (2006). Diversity and variation in biomechanical exposure: What is it, and why would we like to know? *Applied Ergonomics*, *37*(4), 419–427.

Mathiassen, S. E., & Winkel, J. (1996). Physiological comparison of three interventions in light assembly work: Reduced work pace, increased break allowance and shortened working days. *International Archives of Occupational and Environmental Health*, *68*(2), 94–108.

Maton, B. (1981). Human motor unit activity during the onset of muscle fatigue in submaximal isometric isotonic contraction. *European Journal of Applied Physiology and Occupational Physiology*, *46*(3), 271–281.

Merletti, R., Knaflitz, M., & DeLuca, C. J. (1992). Electrically evoked myoelectric signals. *Critical Reviews in Biomedical Engineering*, *19*(4), 293–340.

Merletti, R., Lo Conte, L. R., & Orizio, C. (1991). Indices of muscle fatigue. *Journal of Electromyography and Kinesiology*, *1*(1), 20–33.

Möller, T., Mathiassen, S. E., Franzon, H., & Kihlberg, S. (2004). Job enlargement and mechanical exposure variability in cyclic assembly work. *Ergonomics*, *47*(1), 19–40.

Moritani, T., Muro, M., & Nagata, A. (1986). Intramuscular and surface electromyogram changes during muscle fatigue. *Journal of Applied Physiology*, *60*(4), 1179–1185.

Moritani, T., Stegeman, D., & Merletti, R. (2004). Basic physiology and biophysics of EMG signal generation. In R. Merletti & P. Parker (Eds.), *Electromyography: Physiology, engineering, and noninvasive applications* (pp. 1–20). Hoboken, New Jersey: John Wiley & Sons, Inc.

Muggleton, J. M., Allen, R., & Chappell, P. H. (1999). Hand and arm injuries associated with repetitive manual work in industry: a review of disorders, risk factors and preventive measures. *Ergonomics*, *42*(5), 714–739.

Neumann, W. P., Ekman, M., & Winkel, J. (2009). Integrating ergonomics into production system development - The Volvo Powertrain case. *Applied Ergonomics*, *40*(3), 527–537.

Nordander, C., Ohlsson, K., Akesson, I., Arvidsson, I., Balogh, I., Hansson, G.-A., … Skerfving, S. (2009). Risk of musculoskeletal disorders among females and males in repetitive/constrained work. *Ergonomics*, *52*(10), 1226–1239.

Nordander, C., Ohlsson, K., Balogh, I., Hansson, G. Å., Axmon, A., Persson, R., & Skerfving, S. (2008). Gender differences in workers with identical repetitive industrial tasks: Exposure and musculoskeletal disorders. *International Archives of Occupational and Environmental Health*, *81*(8), 939–947.

Petit, A., Ha, C., Bodin, J., Rigouin, P., Descatha, A., Brunet, R., … Roquelaure, Y. (2015). Risk factors for carpal tunnel syndrome related to the work organization: A prospective surveillance study in a large working population. *Applied Ergonomics*, *47*(0), 1–10.

Rempel, D. (1995). Musculoskeletal loading and carpal tunnel pressure. In S. L. Gordon, S. J. Blair, & L. J. Fine (Eds.), *Repetitive motions disorders of the upper extremity* (pp. 123–133). Rosemont IL: American Academy of Orthopaedic Surgeons.

Sauter, S. L., Brightwell, W. S., Colligan, M. J., Joseph J. Hurrell, J., Katz, T. M., LeGrande, D. E., … Tetrick, L. E. (2002). *The changing organization of work and the safety and health of working people*. Cincinnati: National Institute for Occupational Safety and Health.

Seghers, J., Jochem, A., & Spaepen, A. (2003). Posture, muscle activity and muscle fatigue in prolonged VDT work at different screen height settings. *Ergonomics*, *46*(7), 714–730.

Shah, R., & Ward, P. T. (2007). Defining and developing measures of lean production. *Journal of Operations Management*, *25*(4), 785–805.

Sjøgaard, G., Lundberg, U., & Kadefors, R. (2000). The role of muscle activity and mental load in the development of pain and degenerative processes at the muscle cell level during computer work. *European Journal of Applied Physiology*, *83*(2-3), 99–105.

Soderberg, G. L. (Ed.). (1992). *Selected topics in surface electromyography for use in the occupational setting: expert perspectives*. Cincinnati: National Institute for Occupational Safety and Health.

Søgaard, K., Blangsted, A. K., Jørgensen, L. V., Madeleine, P., & Sjøgaard, G. (2003). Evidence of long term muscle fatigue following prolonged intermittent contractions based on mechano- and electromyograms. *Journal of Electromyography and Kinesiology*, *13*(5), 441–450.

Søgaard, K., Gandevia, S. C., Todd, G., Petersen, N. T., & Taylor, J. L. (2006). The effect of sustained low-intensity contractions on supraspinal fatigue in human elbow flexor muscles. *The Journal of Physiology*, *573*(2), 511–523.

Srinivasan, D., & Mathiassen, S. E. (2012). Motor variability in occupational health and performance. *Clinical Biomechanics*, *27*(10), 979-993.

Thomsen, J. F., Hansson, G. Å., Mikkelsen, S., & Lauritzen, M. (2002). Carpal tunnel syndrome in repetitive work: A follow-up study. *American Journal of Industrial Medicine*, *42*(4), 344–353.

Thomsen, J. F., Mikkelsen, S., Andersen, J. H., Fallentin, N., Loft, I. P., Frost, P., … Overgaard, E. (2007). Risk factors for hand-wrist disorders in repetitive work. *Occupational and Environmental Medicine*, *64*(8), 527–533.

Treaster, D. E., & Burr, D. (2004). Gender differences in prevalence of upper extremity musculoskeletal disorders. *Ergonomics*, *47*(5), 495–526.

Vøllestad, N. K. (1997). Measurement of human muscle fatigue. *Journal of Neuroscience Methods*, *74*(2), 219–227.

Wearing, S. C., Hennig, E. M., Byrne, N. M., Steele, J. R., & Hills, A. P. (2006). Musculoskeletal disorders associated with obesity: A biomechanical perspective. *Obesity Reviews*, *7*(3), 239-250.

Wells, R., Mathiassen, S. E., Medbo, L., & Winkel, J. (2007). Time-A key issue for musculoskeletal health and manufacturing. *Applied Ergonomics*, *38*(6), 733–744.

Wells, R., McFall, K., & Dickerson, C. R. (2010). Task selection for increased mechanical exposure variation: relevance to job rotation. *Ergonomics*, *53*(3), 314–323.

Wells, R., Van Eerd, D., & Hägg, G. (2004). Mechanical exposure concepts using force as the agent. *Scandinavian Journal of Work, Environment and Health*, *30*(3), 179-190.

Westgaard, R. H., & Winkel, J. (1997). Ergonomic intervention research for improved musculoskeletal health: A critical review. *International Journal of Industrial Ergonomics*, *20*(6), 463-500.

Westgaard, R. H., & Winkel, J. (2011). Occupational musculoskeletal and mental health: Significance of rationalization and opportunities to create sustainable production systems - A systematic review. *Applied Ergonomics*, *42*(2), 261–96.

Wild, D., Grove, A., Martin, M., Eremenco, S., McElroy, S., Verjee-Lorenz, A., & Erikson, P. (2005). Principles of good practice for the translation and cultural adaptation process for patient-reported outcomes (PRO) measures: Report of the ISPOR Task Force for Translation and Cultural Adaptation. *Value in Health*, *8*(2), 94–104.

Willliams, C., & Ratel, S. (Eds.). (2009). *Human muscle fatigue*. Abingdon, Oxon: Abingdon, Oxon: Routlegde.

Winkel, J., & Mathiassen, S. E. (1994). Assessment of physical work load in epidemiologic studies: concepts, issues and operational considerations. *Ergonomics*, *37*(6), 979–988.

Winkel, J., & Westgaard, R. (1992). Occupational and individual risk factors for shoulder-neck complaints: Part II — The scientific basis (literature review) for the guide. *International Journal of Industrial Ergonomics*, *10*(1–2), 85–104.

Winkel, J., & Westgaard, R. H. (2008). Risk factors of occupational MSDs and potential solutions: past, present and future. *HESA Newsletter*, *34*, 3–7.

Womack, S. K., Armstrong, T. J., & Liker, J. K. (2009). Lean job design and musculoskeletal disorder risk: A two plant comparison. *Human Factors and Ergonomics In Manufacturing*, *19*(4), 279–293.

Zartarian, V. G., Ott, W. R., & Duan, N. (1997). A quantitative definition of exposure and related concepts. *Journal of Exposure Analysis and Environmental Epidemiology*, *7*(4), 411–437.

CHAPTER 2: Objectives, Methodological Aspects and Thesis Structure

2.1. Objectives

Given the numerous gaps in knowledge concerning the influence of temporal organization of work on musculoskeletal health, particularly in real work conditions and considering that muscle fatigue represents a precursor of WMSDs, the main objective of this thesis was to determine the influence of temporal aspects of work on fatigue during assembly work in a real occupational setting.

To achieve this main goal, specific objectives were established as follows:

1. determine the effects of work duration on EMG manifestation of muscle fatigue and on perceived fatigue;
2. determine the effects of job rotation on EMG manifestation of muscle fatigue and on position sense acuity of the wrist;
3. assess the ability of an inertial motion capture system to quantify upper-limb mechanical exposure between two assembly lines with different mechanization levels in realistic conditions;
4. develop a cross-cultural adaptation of an instrument to measure work-related perceived fatigue for the Portuguese language and study the reliability and validity of the data gathered with this instrument.

2.2. Methodological Considerations

The present research was conducted at a multinational corporation devoted to the production of mechanical cables for automotive industry. This company is located in Porto region and integrated two production plants and works for 24 hours/day. To become a supplier, it is mandatory to have the ISO 9001:2008 and ISO TS: 16949 2011 certification. It is also certified by ISO 14001:2004 (Environment Management System) and by OHSAS 18001:2007 (Occupational Health and Safety Management System). In addition, it has implemented Lean Production System (LPS).

The first step of this research involves an evaluation of the sample in terms of their demographic characteristics, health status, musculoskeletal health symptoms and body composition. One hundred thirty-four women assembly workers (exposed group) and thirty four women of a control group (non exposed group) were evaluated. Demographic characteristics and health status were collected through a questionnaire developed for the purpose (Appendix A). The Portuguese version of the standardized Nordic musculoskeletal questionnaire (Mesquita, Ribeiro, & Moreira, 2010) to analyze musculoskeletal symptoms was used (Appendix B). Body composition was determined by bioelectric impedance analysis (BIA) using a portable body consistency monitor (InBody 230, Biospace Co., Ltd. USA). BIA is a simple and noninvasive technique which was recently proposed to investigate body composition in field studies. This technique allows to calculate the amount of body fat, fat-free mass, and the amount of body water (Foster & Lukaski, 1996; Roubenoff, Dallal, & Wilson, 1995).

Assembly workers that participated in this first stage were distributed by two production plants and by three work shifts - morning shift: 6 a.m. to 2 p.m.; afternoon shift: 2 p.m. to 10 p.m.; night shift: 10 p.m. to 6 a.m.

Additionally, the need to rate perceived fatigue in the next stages of this work, and the fact that there is no Portuguese version of self-report instruments regarding occupational fatigue as a multidimensional state, SOFI seemed to be an adequate tool to be used. In fact SOFI proposed by Åhsberg (2000), has been used in the last fifteen years as a measure of perceived fatigue in occupational context by several authors. Considering the importance that reliable and valid instruments have for understanding and assess fatigue, a study regarding the translation and cultural adaptation process and analysis of psychometric properties of this instrument, was conducted in parallel. For this purpose, SOFI was applied to 290 workers of the production section at the end of their shifts (218 questionnaires were considered valid). The Portuguese version of SOFI is in the Appendix C. In this thesis was also used Borg CR-10 scale to analyzed perceived exertion during work (Appendix D).

In order to achieve the other objectives of this thesis, three studies involving quantification of muscle activity (surface EMG), position sense tests (electrogoniometer) and kinematic measures (full-body inertial measurement system) were conducted. With the exception of kinematic measures, the other evaluations did not interfere with the normal working time.

There are many factors that can influence the worker´s fatigue development, which can ultimately affect performance and the risk of injury. The mechanisms that cause fatigue, are strictly related to the type and intensity of task performed (Bigland-Ritchie, Rice, Garland, & Walsh, 1995). However, considering that the decline in force or force-generating capacity can have its origin at many levels of the neural axis, individuals with any neurological disorders have a reduced ability to maintain sustained voluntary contractions and so the changes in the muscle are limited. Consequently changes in the surface EMG, in terms of decline in muscle-fiber conduction and lowering of frequency content will also be very limited (Zwarts, Stegeman, & van Dijk, 2004).

Musculoskeletal discomfort and pain are often reported by workers while performing their tasks. Szeto, Straker, & O'Sullivan (2005) and Szeto & Lin (2011) found that symptomatic individuals altered their muscle recruitment pattern and had higher levels of muscle activation than asymptomatic individuals. Alterations of motor control mechanisms in pain conditions may contribute to WMSDs (Madeleine, 2010).

The effect of work experience on motor activity can be considered an important factor to understand motor adaptations as well as fatigue mechanisms (muscle activity). Inexperienced workers seemed to have lower motor adaptation of tasks (higher work cycle time), more pronounced EMG signs of fatigue and, consequently a higher risk of muscle injury, than highly experienced workers (Delisle, Larivière, Plamondon, & Imbeau, 2006; Madeleine, Lundager, Voigt, & Arendt-Nielsen, 2003; Parakkat, Yang, Chany, Burr, & Marras, 2007; Yang, Chany, Parakkat, Burr, & Marras, 2007).

Considering all factors enumerated above, from the sample evaluated in the first stage of this research (134 individuals (exposed group) and 34 individuals (non exposed group)), individuals with any musculoskeletal or neurological disease, musculoskeletal symptoms and/or work experience less than 12 months were excluded. Figure 6 shows the distribution of the participants in our studies.

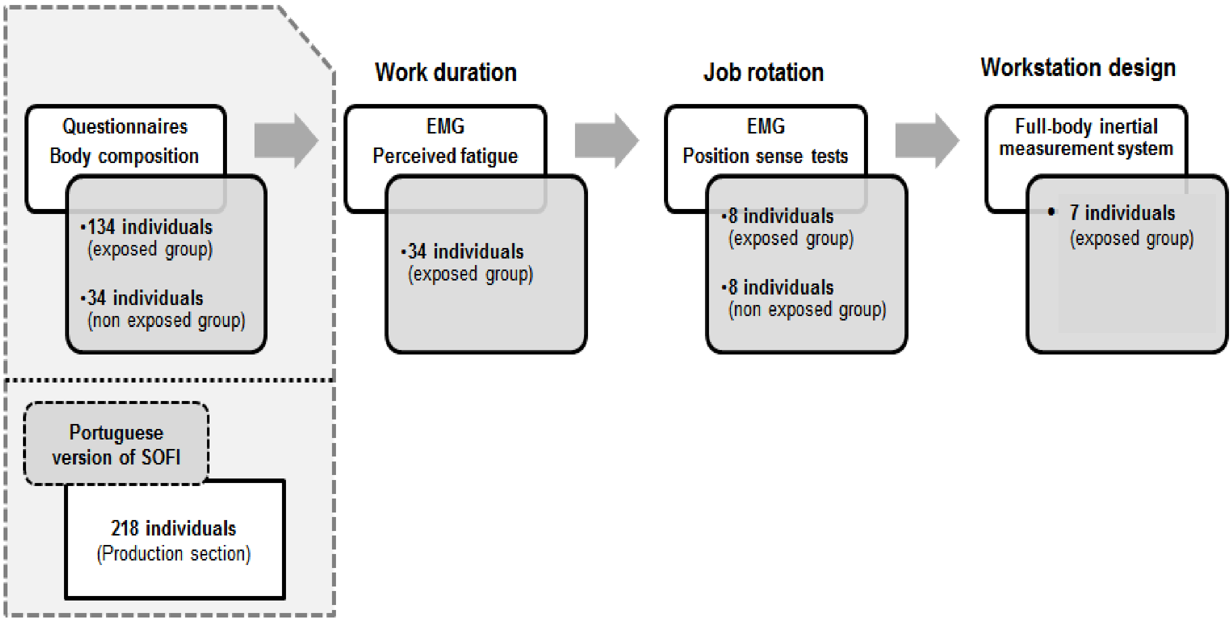


Figure 6. Number of participants in each study.

2.3. Thesis Organization

The thesis is divided into eight chapters. The content of each chapter is given below.

Chapter 1 includes a general introduction, which describes the state-of-the-art, relevance and motivation for this work.

Chapter 2 presents the description of the objectives, methodological considerations and thesis organization.

Chapter 3 presents a manuscript that reviews systematically the scientific literature concerning the influence of the task design (related to job rotation and temporal organization of work) on the muscle fatigue in low-force work development in workplaces or experimental settings.

Chapter 4 presents a manuscript regarding the psychometric properties of the Portuguese version of the Swedish Occupational Fatigue Inventory (SOFI) among industrial workers. This scale was used to assess perceived fatigue in the study described in Chapter 5.

Chapter 5 provides a manuscript regarding the investigation of muscle fatigue over a working day in a real-life occupational setting using the EMG signal of the extensor carpi radialis and flexor carpi radialis muscle during assembly work. Additionally, the relationship between EMG indicators of fatigue and workers' perceived fatigue was determined.

Chapter 6 comprises a manuscript that investigated the effect of job rotation on wrist muscle fatigue among experienced assembly workers and how muscle fatigue affected wrist position sense acuity.

Chapter 7 presents a manuscript that quantifies the differences in the upper-limb mechanical exposure between two assembly lines with different mechanization levels. The ability and performance of an inertial motion capture system in realistic conditions was also tested.

Finally, **Chapter 8** presents the overall discussion of the results, the main findings and conclusions and underlines future perspectives for research indicating possible lines of work to complement and further development of the studies undertaken during this thesis.

The structure of the manuscripts was maintained according to the journal guidelines in which they were submitted, although the reference style was uniformed to APA (American Psychological Association) 6th edition. Tables and figures were numbered consecutively throughout the thesis.

2.4. References

Åhsberg, E. (2000). Dimensions of fatigue in different working populations. *Scandinavian Journal of Psychology*, *41*(3), 231–241.

Bigland-Ritchie, B., Rice, C. L., Garland, S. J., & Walsh, M. L. (1995). Task-dependent factors in fatigue of human voluntary contractions. *Advances in Experimental Medicine and Biology*, *384*, 361–380.

Delisle, A., Larivière, C., Plamondon, A., & Imbeau, D. (2006). Comparison of three computer office workstations offering forearm support: impact on upper limb posture and muscle activation. *Ergonomics*, *49*(2), 139–160.

Foster, K. R., & Lukaski, H. C. (1996). Whole-body impedance - What does it measure? *American Journal of Clinical Nutrition*, *64*(Suppl. 3), 388S-396S.

Madeleine, P. (2010). On functional motor adaptations: From the quantification of motor strategies to the prevention of musculoskeletal disorders in the neck-shoulder region. *Acta Physiologica*, *199*(Suppl. 679), 1–46.

Madeleine, P., Lundager, B., Voigt, M., & Arendt-Nielsen, L. (2003). Standardized low-load repetitive work: Evidence of different motor control strategies between experienced workers and a reference group. *Applied Ergonomics*, *34*(6), 533–542.

Mesquita, C., Ribeiro, J., & Moreira, P. (2010). Portuguese version of the standardized Nordic musculoskeletal questionnaire: cross cultural and reliability. *Journal of Public Health*, *18*(5), 461–466.

Parakkat, J., Yang, G., Chany, A. M., Burr, D., & Marras, W. S. (2007). The influence of lift frequency, lift duration and work experience on discomfort reporting. *Ergonomics*, *50*(3), 396–409.

Roubenoff, R., Dallal, G. E., & Wilson, P. W. F. (1995). Predicting body fatness: The body mass index vs estimation by bioelectrical impedance. *American Journal of Public Health*, *85*(5), 726–728.

Szeto, G. P. Y., & Lin, J. K. M. (2011). A study of forearm muscle activity and wrist kinematics in symptomatic office workers performing mouse-clicking tasks with different precision and speed demands. *Journal of Electromyography and Kinesiology*, *21*(1), 59–66.

Szeto, G. P. Y., Straker, L. M., & O'Sullivan, P. B. (2005). EMG median frequency changes in the neck–shoulder stabilizers of symptomatic office workers when challenged by different physical stressors. *Journal of Electromyography and Kinesiology*, *15*(6), 544–555.

Yang, G., Chany, A. M., Parakkat, J., Burr, D., & Marras, W. S. (2007). The effects of work experience, lift frequency and exposure duration on low back muscle oxygenation. *Clinical Biomechanics*, *22*(1), 21–27.

Zwarts, M. J., Stegeman, D. F., & van DijK, J. G. (2004). Surface EMG applications in neurology. In R. Merletti & P. A. Parker (Eds.), *Electromyography: Physiology, engineering, and non-invasive applications* (pp. 323–342). Hoboken, New Jersey: John Wiley & Sons, Inc.

CHAPTER 3: The influence of task design on upper limb muscles fatigue during low-load repetitive work: a systematic review

Abstract

Ergonomic interventions such as increased scheduled breaks or job rotation have been proposed to reduce upper limb muscle fatigue in repetitive low-load work. This review was performed to summarize and analyze the studies investigating the effect of job rotation and work-rest schemes, as well as, work pace, cycle time and duty cycle, on upper limb muscle fatigue. The effects of these work organization factors on subjective fatigue or discomfort were also analyzed. This review was based on relevant articles published in PubMed, Scopus and Web of Science. The studies included in this review were performed in humans and assessed muscle fatigue in upper limbs. 14 articles were included in the systematic review. Few studies were performed in a real work environment and the most common methods used to assess muscle fatigue were surface electromyography (EMG). No consistent results were found related to the effects of job rotation on muscle activity and subjective measurements of fatigue. Rest breaks had some positive effects, particularly in perceived discomfort. The increase in work pace reveals a higher muscular load in specific muscles. The duration of experiments and characteristics of participants appear to be the factors that most have influenced the results. Future research should be focused on the improvement of the experimental protocols and instrumentation, in order to the outcomes represent adequately the actual working conditions.

Relevance to industry: Introducing more physical workload variation in low-load repetitive work is considered an effective ergonomic intervention against muscle fatigue and musculoskeletal disorders in industry. Results will be useful to identify the need of future research, which will eventually lead to the adoption of best industrial work practices according to the workers capabilities.

Keywords: fatigue, repetitive work, low-load work, upper limbs

3.1. Introduction

Muscle fatigue is a complex phenomenon that has been suggested to be an important precursor for work-related upper-limb musculoskeletal disorders (Ding, Wexler, & Binder-Macleod, 2000; Nussbaum, Clark, Lanza, & Rice, 2001; Lomond & Cote, 2011). Several authors have reported that repetitive manual work is a risk factor associated with wrist and hand disorders, such as tendon-related disorders, carpal tunnel syndrome (CTS) and cramping of the hand and forearm (Muggleton, Allen, & Chappell, 1999; Viikari-Juntura & Silverstein, 1999; Hansson et al., 2000). According to Thomsen, Hansson, Mikkelsen, & Lauritzen (2002), an increase duration of repetitive non-forceful work results in an increased risk of CTS. The effects of fatigue on functional capacity include reductions in maximal isometric force and power output (Vollestad, 1997; Blangsted, Sjøgaard, Madeleine, Olsen, & Søgaard, 2005; Enoka & Duchateau, 2008; Fuller, Lomond, Fung, & Cote, 2009). Muscle fatigue can occur as a result of alterations in the central nervous system and/or neuromuscular junction (central fatigue) or in the muscle fiber (peripheral fatigue) (Willliams, 2009). These mechanisms are dependent on the intensity, duration, the predominantly recruited muscle fiber type and type of contraction, as well as individual capacity and environmental conditions (McLean, Tingley, Scott, & Rickards, 2000).

In the industrial environment, it is essential to reduce the occurrence of muscle fatigue because it has a great impact on task performance. Thus, the major challenge for ergonomics is to design the work in order to prevent work-musculoskeletal disorders (WMSD) and with no negative impact on production quality and productivity (Wells, Mathiassen, Medbo, & Winkel, 2007). At present, repetitiveness and monotonous work are common in industries with automated work processes. According to Eurofound (2010), more than 60% of workers currently report performing repetitive hand or arm movements at work. Assembly tasks are an example of work where the procedures are strictly standardized with short cycle times (less than 30s), little task variation and reduced breaks or pauses. Furthermore, there is some evidence that upper limb WMSD risk factors are related to characteristics of the assembly task (van der Windt *et al.*, 2000).

Despite numerous studies suggesting that muscle fatigue can be developed during highly repetitive low-load tasks (< 20% maximal voluntary contraction (MVC)), there are several gaps in knowledge concerning the influence of task design, which includes work organization factors such as work duration (hours of work and shift work), duty cycle, cycle time, work pace and job rotation, on fatigue and musculoskeletal health. Changes in temporal organization of work (e.g. change in cycle time) or implementation of job rotation in workplaces may increase physical workload variation and has been proposed to minimize injury risk and fatigue in jobs with repetitive tasks (Fallentin, Viikari-Juntura, Wærsted, & Kilbom, 2001; Aptel, Cail, Gerling, & Louis, 2008; Wells, McFall, & Dickerson, 2010).

Thus, it is very important to study the risk factors associated with task design on the development of disorders in the wrists and hands in highly repetitive hand–arm work.

The purpose of this article is to review the scientific literature concerning the influence of the task design (related to temporal organization of work and job rotation) on muscle fatigue in low-load work development in workplaces or experimental settings.

3.2. Methods

3.2.1. Search strategy

The systematic search was focused on literature pertaining to the effect of task design on the development of muscle fatigue in upper limbs in workplaces or experimental settings (simulated occupational tasks). The search strategy consisted of a comprehensive search that could locate the widest spectrum of articles for consideration and was performed in selected electronic databases, namely: PubMed, Scopus and Web of Science, from the earliest date available in the database to 31st December 2013. Based on the electronic database used, the search terms were as follows: “muscle fatigue” combined with another term such as “upper limbs”, “forearm muscles”, “workload”, “work-related musculoskeletal disorders”, “repetitive movements”, “repetitive work”, “assembly work”, “low-force work”, “low-intensity work”, “low-load work“, “work cycle time”, “wrist”, “work rest pattern”, “rest breaks”, “work duration”, “work pace”, “job rotation” and “task design”. The Appendix E describe the search strategies in each database.

3.2.2. Screening criteria

Articles obtained by the systematic search were exported to EndNote library X4 (Thomson corporation) and duplicates were removed. Exclusion of irrelevant articles was performed using a three-step systematic approach: 1) titles were examined for relevance; 2) abstracts were then considered (in particular, objectives and methods); and 3) the full text article was retrieved and considered. If there was any uncertainty about content or if a title and abstract did not provide sufficient information to determine whether the inclusion/selection criteria were met, then the article proceeded to the next step. Studies were automatically excluded if one of these conditions were met: 1) studies not published in peer-reviewed journals written in English 2) studies reviewing literature; 3) studies where the intensity of the workload (maximal EMG activity) was higher than 30% MVC; 4) studies that did not apply an objective measuring method to assess the development of fatigue over time; 5) studies comparing different tools to assess muscle fatigue; 6) studies defining muscle fatigue models and/or acceptable limits; 7) studies assessing neuromuscular responses; and 8) studies investigating muscle fatigue caused by torque reaction forces.

3.2.3. Eligibility criteria

Studies were included in the review if the following conditions were met: (1) those that considered the development of muscle fatigue in upper limbs (including the forearm, arm and shoulder muscles) during repetitive low-load work; (3) those that only investigated the effect of temporal organization of work and job rotation schemes on upper limb muscle fatigue; and (4) those that assessed muscle fatigue in occupational activities performed in real work conditions and/or simulated occupational tasks. Two reviewers evaluated the eligibility of all articles, and disagreements were resolved by consulting a third reviewer.

3.2.4. Data extraction and quality assessment

From the studies selected after eligibility, the following data (when available) were extracted: size (N) and characteristics of the sample (gender and age), muscle group under study, type of tasks, experimental conditions, methods and/or techniques used to assess fatigue, study design, main outcomes for objective and subjective measure of fatigue and statistical analysis. Data from each study were extracted by one of the reviewers and confirmed by the other. The information obtained from the included studies was organized descriptively in tables.

A quality assessment list was constructed using criteria from Greenhalgh, Robert, Bate, Macfarlane, & Kyriakidou (2005) and from von Elm et al. (2008), which were adapted to the specific aim of this review. To judge quality, information regarding participant's source (eligibility criteria), definition of variables and their methods of measurement/assessment, description of efforts to address potential sources of bias, outcome data, limitations and generalizability of each study, was collected. For all of these items, specific criteria assessment were defined (details are given in Appendix F). Two reviewers independently assessed the quality of each study by scoring each criteria as positive (+), negative (-), or unclear (?). Disagreements were resolved by consensus. The quality score for every study was calculated by summing the number of positive criteria.

3.3. Results and Discussion

The search strategy identified a total of 1748 citations before duplicates removal. After confirming the duplicates (n=779) and excluding the non-relevant ones (n=895), 74 full-text articles were analyzed. After application of the eligibility criteria while considering the full text, another 60 articles were excluded. A total of 14 experimental studies conducted in the laboratory or in the field were considered for the final analysis. Figure 7 displays the flowchart of the search strategy.

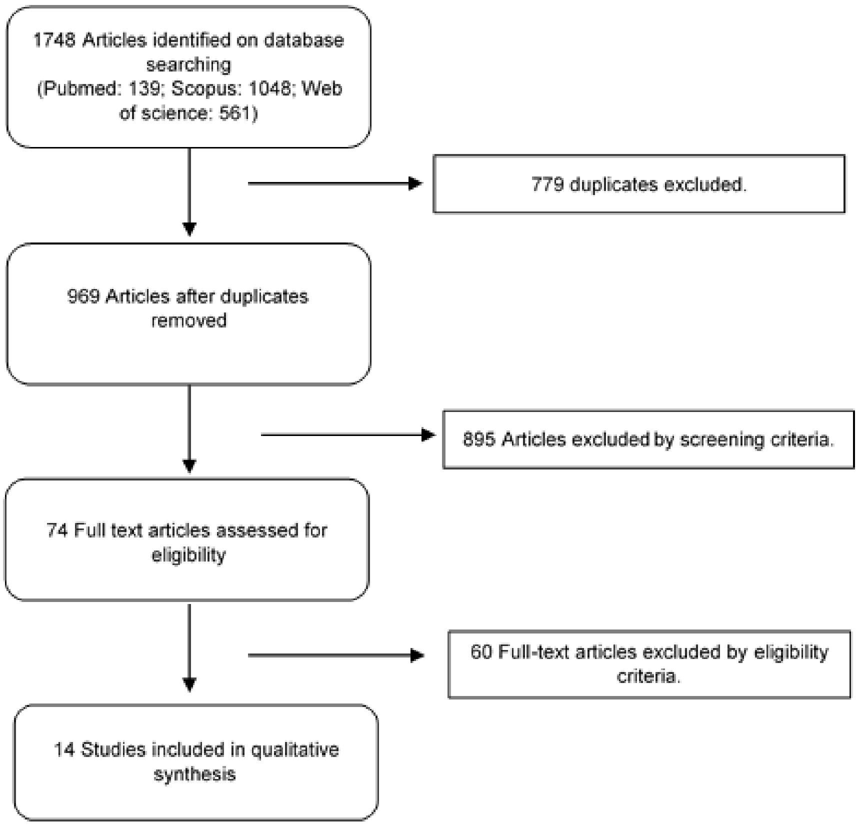


Figure 7. Article screening process.

The 14 articles included a total of 246 participants, of which 45.1% were females. Our search identified 12 studies on tasks that were simulated in the laboratory (Horton, Nussbaum, & Agnew, 2012; Gooyers & Stevenson, 2012; Bosch, Mathiassen, Visser, de Looze, & van Dieen, 2011; Keir, Sanei, & Holmes, 2011; Wells, *et al*., 2010; Raina & Dickerson, 2009; Iridiastadi & Nussbaum, 2006; Balci & Aghazadeh, 2004; Gerard, Armstrong, Martin, & Rempel, 2002; McLean, Tingley, Scott, & Rickards, 2001; Mathiassen & Winkel,1996; Sundelin, 1993) and 2 studies on real-life occupational settings (Bosch, De Looze, & Van Dieen, 2007; Christensen, Sogaard, Pilegaard, & Engineer, 2000). In general, the laboratory studies had small-sized sample groups.

The task characteristics included job rotation in 4 studies (Horton, *et al*., 2012; Gooyers & Stevenson, 2012; Keir, *et al*., 2011; Wells, *et al*., 2010; Raina & Dickerson, 2009) work-rest schemes (or pauses or breaks) schedules in 4 studies (Balci & Aghazadeh, 2004; McLean, *et al*., 2001; Christensen, *et al*., 2000; Sundelin, 1993) and 6 studies investigating the effects of work pace, cycle time, duty cycle and work duration (Gooyers & Stevenson, 2012; *Bosch, et al*., 2011; Bosch, *et al*., 2007; Iridiastadi & Nussbaum, 2006; Gerard *et al*., 2002; Mathiassen & Winkel,1996). Only one study did not use electromyography (EMG) as an objective measuring method to assess the development of fatigue (Wells *et al*., 2010). All tasks included in this review were considered to be repetitive work categorized in dynamic (e.g., assembly work) or intermittent static work (e.g. handgrip exercise) (Kilbom, 1994). Forearm muscles were studied in eight articles.

The resulting 14 articles are presented in Table 1 (effects of job rotation), Table 2 (effects of work/rest schemes) and Table 3 (effects of work pace, cycle time and duty cycle). In each article analyzed, the experimental conditions were identified with a “C” letter and followed by a number. Regarding the main outcomes of the parameters for each experimental condition they are presented in descending order (e.g., C2>C1>C3).

3.3.1. Effects of job rotation

None of the rotation studies (see Table 1) showed that the increase in task variation had a significant effect on the objective and subjective manifestation of muscle fatigue. Horton, *et al*. (2012) found that rotation frequency and task order at higher exertion levels presented an increase in EMG amplitude and a decrease in EMG mean power frequency (EMG MPF). However, at lower exertion tasks, the results were opposite to the expected. For low-load tasks, Yung, Mathiassen, & Wells (2012) suggested that time-varying force may be a useful intervention to reduce local fatigue. Keir, *et al*. (2011) demonstrated that only the anterior deltoid, trapezius and lower erector *spinae* benefited from rotating lifting and gripping tasks. However, forearm extensor muscles benefited from the task order, because they presented significantly higher levels of activity (10^{th} (static level) and 50^{th} (median level) percentile activity levels) for gripping-gripping compared to lifting-gripping, while for lifting-lifting, they presented a significantly lower activity compared to the griping-lifting condition. Indeed, these muscles are required for both tasks, which contrasts with the principle of job rotation, which intends to promote alternating tasks to provide rest periods to muscle groups and to reduce overall muscle activity, thereby reducing muscular overload (Mathiassen, 2006). A potential determinant of these results in both articles could be the variation of intensity of work tasks across conditions. Raina & Dickerson (2009) demonstrated that performing continuous shoulder abduction (BB) was more fatiguing than rotation between shoulder abduction and flexion. In this case, integrated EMG for shoulder abduction alone was significantly higher than for all other task combinations and EMG MPF values were lower. Wells, *et al*., (2010) presented positive results of an increase in grip strength as a consequence of prehensile activity variation despite the high functional similarity of tasks (both tasks utilized a common group of musculoskeletal tissues), particularly between power grip/ pulp pinch grip (75.7%) and lateral pinch/pulp pinch (66.3%). Interestingly, only this job rotation study did not implement a subjective measurement of fatigue. In general, the subjective rate of fatigue increases across time in three of the reviewed studies. The effect of change intensity in the subjective feelings was reported by Horton, *et al*. (2012), and these results showed that during the task with more muscular demand (30% MVC), the rating of perceived exertion (RPE) increases. In contrast, for the lowest exertion task (15%), the RPE decrease. Thus, the variation between tasks with different physical exposures reduces the risk of fatigue and consequently WMSD, as recommended by Mathiassen, (2006). However, currently with the intensive production systems, which are characterized by short-cycle tasks and standardized processes (Neumannr, Kihlberg, Medbo, Mathiassen, & Winkel, 2002), it is challenging to identify work tasks that overload different muscle groups. The findings of Keir, *et al.* (2011) and Raina & Dickerson (2009) were similar because the RPE was lower when the participants started with the less strenuous task.

Table 1. Overview of results of “effects of rotation”.

Reference	Sample	Muscle group	Task	Conditions	Fatigue measure	Response variables and main outcomes	
						Objective Fatigue	***Subjective fatigue***
Horton, et al. (2012)	General population *N* = 12 (6M, age: 22.5 ±1.9 years). (6F, age: 23.0±1.97 years).	Middle deltoid muscle	Repetitive static shoulder abduction tasks (60 min.).	Two exertion levels: 15% MVC – “L” lower exertion task. 30% MVC - “H” higher exertion task. C1: No rotation LLLL C2: No rotation HHHH C3: One rotation LH C4: One rotation HL C5: Three rotation LHLH C6: Three rotation HLHL	EMG RPD	EMG amplitude (%RVE): C3-C6 > C1 (*p*<0.001) C2 > C3-C6 (*p*<0.001) C2 > C1 (*p*<0.001) C3 > C4 (*p*=0.39) C5 = C6 (*p*=0.88) EMG MPF (%RVE):: C1 > C3-C6 (p<0.001) C3-C6 > C2 (n.d) C1 > C2 (*n.d*) C3 = C4 (*n.d*) C5 > C6 (*n.d*) DSI (%RVE): : C3-C6 > C1 (*p*<0.001) C2 > C3-C6 (*p*<0.001) C2 > C1 (*p* = 0.0005) C3 > C4 (*p* = 0.25) C6 > C5 (*p*=0.096)	Mean RPD: C3-C6 > C1 (p=0.0038) (shoulder) C3-C6 > C1 (p=0.038) (upper arm) C2 > C3-C6 (p=0.001) (shoulder) C2 > C3-C6 (p=0.0006) (upper arm) C2 > C1 (p<0.0001) (shoulder) C2 > C1 (p<0.0001) (upper arm) C3 > C4 (p = 0.82) (shoulder) C3 < C4 (p=0.39) (upper arm) C6 > C5 (p = 0.091) (shoulder) C6 > C5 < (p=0.076) (upper arm) Peak RPD: C3-C6 > C1 (p<0.0001) (shoulder) C3-C6 > C1 (p=0.0003) (upper arm) C2 > C3-C6 (p=0.007) (shoulder) C2 > C3-C6 (p=0.0004) (upper arm) C2 > C1 (p<0.0001) (shoulder) C2 > C1 (p<0.0001) (upper arm) C4 > C3 (p = 0.54) (shoulder) C4 > C3 (p=0.34) (upper arm) C5 > C6 (p = 0.56) (shoulder) C6 > C5 < (p=0.51) (upper arm)
Keir, et al. (2011)	University population *N* = 10 (10M, age: 21.8±2.2 years)	Upper erector spinae (UE); lower erector spinae (LE); trapezius (TR); anterior deltoid (AD); extensor carpi radialis (ECR); flexor carpi radialis (FCR); flexor digitorum superficialis (FDS) and extensor digitorum communis (ED).	Lifting/Lowering task (L) - 12 kg box (handles 0.50 m apart), at a rate 6 per minute, 10 s cycle (5 s for task with 5 s for rest); gripping task (G) at 20%, at a rate 6 per minute, 10 s cycle (5 s for task with 5 s for rest).	C1: No rotation: LL (30 min.) C2: No rotation: GG (30 min.) C3: Rotation: L (15 min.) and G (15 min.) C4: Rotation: G (15 min.) and L (15 min.)	EMG RPE	EMG APDF10th%: C2 (ECR) > C1 (ECR) and C3 (ECR) (*p*=0.011) C2 (ED) > C1 (ED) and C3 (ED) (*p*=0.001) EMG APDF50th%: C2 (ECR) > C1 (ECR) and C3 (ECR) (*p*=0.030) C2 (ED) > C1 (ED) and C3 (ED) (*p*=0.030) C2 (FDS) > C1 (FDS) and C3 (FDS) (*p*=0.030) C1(ECR) > C4 (ECR) (*p*=0.030) C1(ED) > C4 (ED) (*p*=0.030) EMG APDF90th%: C1, C3 and C4 > C2 (ED) (*p*=0.028) C1, C3 and C4 > C2 (FCR) (*p*=0.028) EMG gaps: C1 and C3 > C4 > C2 (ED) (n.s.) C1 > C3 > C4 > C2 (ECR) (n.s.) C3 > C4 > C1 > C2 (FDS) (n.s.) C3 > C1 > C4 > C2 (FCR) (n.s.)	RPE: C1 > C2 (n.s.) C3 > C4 (n.s)

Reference	Sample	Muscle group	Task	Conditions	Fatigue measure	Response variables and main outcomes	
						Objective Fatigue	***Subjective fatigue***
Wells, et al. (2010)	University population *N* = 25 (age: 20-34 years)	Forearm muscles	Three handgrips: power grip (PG); two finger pulp pinch (PP); lateral pinch (LP) at 30% MVC during 55 s each, followed by a 5 s maximum test task. (sequence: first work task → first test task → second work task → second test task)	15 combinations (2 min. duration): C1. PG, PG, PG, PG C2. PP, PG, PG, PG C3. LP, PG, PG, PG C4. PG, PG, PP, PG C5. PG, PG, LP, PG C6. PP, PP, PP, PP C7. LP, PP, PP, PP C8. PG, PP, PP, PP C9. PP, PP, LP, PP C10. PP,PP, PG, PP C11. LP, LP, LP, LP C12. PP, LP, LP, LP C13. PG, LP, LP, LP C14. LP, LP, PG, LP C15. LP, LP, PG, LP	Hand grip dynamometer	Grip strength: C3, C4, C5, C9, C10 and C15 > C1, C6 and C11 (p<0.05) Functional similarity (%): PG/PP = 75.7 PG/LP = 33.5 LP/PP = 66.3	n.a.
Raina & Dickerson (2009)	University population *N* = 10 (6 M and 4 F, age: 25.7±5.4 years)	Anterior deltoid muscle (AD), middle deltoid muscle (MD) and posterior deltoid muscle (PD)	Two repetitive, unilateral (right side), unloaded arm movements, repeated at a frequency of 0.5Hz. Task combinations: a forward shoulder flexion movement in the sagittal plane (A) and a shoulder abduction movement in the frontal plane (B).	C1: 4 continuous minutes of task A (forward flexion) - AA. C2: 2 minutes of task A (forward flexion), followed by two minutes of task B (abduction in the frontal plane) - AB. C3: 2 minutes of task B (abduction in the frontal plane), followed by two minutes of task A (forward flexion) – BA. C4: 4 minutes of task B (abduction in the frontal plane) - BB.	EMG Force cube RPE	Adjusted means of mEMG (%MVC): C3 > C4 (AD) (n.s.) C4 > C3 = C2 > C1 (MD) (n.s.) C4 > C3 > C2 > C1 (PD) (p<0.05) iEMG (%MVC): AD: n.s. between conditions C4 > C1-C3(MD) (p=0.001) C4 > C1-C3 (PD) (p=0.001) EMG MPF: C2 > C4 (AD) (p<0.05) C2 > C4 (PD) (p<0.05) Maximum elevation force (MVF): n.s between conditions	RPE: C4 = C3 > C2 = C1 (p<0.0003)

Abbreviations: M, male; F, female; s, seconds; MVC, maximum voluntary contraction; RVE, sub-maximal reference contraction; MPF, mean power frequency; DSI, Dimitrov spectral index; RPD, rating of perceived discomfort; APDF, amplitude probability distribution function; RPE, rating of perceived exertion; iEMG, integrated amplitude; mEMG, windowed amplitude; n.a., not applicable; n.d., not defined; n.s., not significant.

3.3.2. Effects of work/rest schemes

In the four studies examined (see Table 2), two of the studies were related to tasks analyzed during computer work. According to Balci & Aghazadeh (2004), the introduction of microbreaks (every 15 min to 30 min of work) contributed to a reduction in discomfort and increased performance. Similar results were confirmed by van den Heuvel, de Looze, Hildebrandt, & Thé (2003) in an office work field study. For EMG measurements, the study by Balci & Aghazadeh (2004) showed that a 60/10 schedule (60 min work/10 min rest) caused the highest load increase in the upper trapezius. McLean, *et al*. (2001) also demonstrated that microbreak protocols had a positive effect on subjective discomfort and did not affect worker productivity. Previous research conducted by Dababneh, Swanson, & Shell (2001) revealed that two experimental rest break schedules did not have a negative effect on production. In the study by McLean *et al*. (2001), wrist extensors presented a higher frequency of mean frequency (MNF) of the myoelectric signal (MES) when “microbreaks” were introduced in 20-min intervals. These results were consistent with those obtained from McLean *et al*. (2000), who found a higher median value of mean frequency for the “break” compared to the “no break” protocol regarding cervical extensors.

In the other two studies, the results of objective manifestation of muscle fatigue in the EMG signals were not consistent. Christensen, *et al*. (2000) found no differences in RMS values, EMG power spectrum and EMG mean power frequency (MPF) between groups with longer and faster breaks. In addition, heart rate and blood pressure did not present significant differences in these two groups. This type of field research has some confounding variables that may have influenced the results, such as duration of tasks and variation of products, but field studies have the advantage of not requiring extrapolation to practice. Sundelin (1993) found objective evidence of muscle fatigue with a decrease in MPF and an increase in RMS amplitude during work with and without breaks in some participants. Furthermore, no differences in ratings of perceived exertion and discomfort between groups were found.

Table 2. Overview of results of "effects of work breaks".

Reference	**Sample**	**Muscle group**	**Task**	**Conditions**	**Fatigue measure**	**Response variables and main outcomes**	
						Objective Fatigue	***Subjective fatigue***
Balci & Aghazadeh (2004)	Students *N* = 10 (10M)	Right upper trapezius (UT) and right arm flexor carpi radialis (FCR).	Video display terminal (VDT) work	C1:15 min.work/microbreaks – cognitive task C2: 30 min.work./5 min.rest – cognitive task C3: 60 min. work/10 min. rest – cognitive task C4:15 min.work/microbreaks – data entry task C5: 30 min.work./5 min.rest – data entry task C6: 60 min. work/10 min. rest – data entry task	EMG Speed Accuracy RPD	Performance (speed and accuracy): C1 and C4 > C3 and C6 (n.d) Muscular Load: C6 > C5 > C4 (UT) (n.d.) C3 > C1> C2 (UT) (n.d.) C3 > C1 > C2 (FCR) (n.d.)	RPD: C6 > C1-C5 for upper extremities (n.d.)
McLean et al. (2001)	Office workers *N* = 15 (15F, age: 23-50 years)	Cervical paraspinal extensors (CPE), lumbar erector spinae (LES), upper trapezius(UT) and wrist extensors (WE)	Computer terminal work (4 weeks)	C1: "No break protocol" C2: "Microbreak protocol" - microbreaks at their own discretion (control) C3: "Microbreak protocol"- microbreaks at 20 min intervals C4: "Microbreak protocol"- microbreaks at 40 min intervals	MES activity VAS score (discomfort) Productivity	Mean of MNF cycles: UT: no protocol effect C3 > C1 (WE) (n.d.) C2 and C4 > C3 (WE) (n.d.) Productivity (number of words typed): C1 > C2 (n.s.) n.s. effect of C3 and C4	VAS score: n.s. between C1 and C2-C4 (shoulder) C1, C2, C4 > C3 (forearm) (n.d.)
Christensen et al. (2000)	Meat cutters *N* = 48 (48M, age: 33.7 years)	Extensor carpi radialis muscle; flexor carpi radialis muscle	Three work tasks: Deboning belly pork – 59,6 s; Deboning shoulders – 111,0 s; Deboning ham – 133,0 s.	C1: "Fast" group (6 M): 68,4 – 85,5% of the mean of work time (higher rest periods). C2: "Slow" group (6M) 121,0 -138,9% of the mean of work time (lowest rest periods).	Heart rate (HR) Blood pressure Hand dynamometer EMG	HR: n.s. between C1 and C2 Blood pressure: n.s. between C1 and C2 Muscular load (Maximal EMG activity %): n.s. between C1 and C2 EMG RMS: n.s. between C1 and C2 EMG MPF: n.s. between C1 and C2 EMG power spectrum: n.s. between C1 and C2 EMG APDF: n.s. between C1 and C2	n.a.

Reference	**Sample**	**Muscle group**	**Task**	**Conditions**	**Fatigue measure**	**Response variables and main outcomes**	
						Objective Fatigue	***Subjective fatigue***
Sundelin (1993)	Students *N* = 12 (12F, age: 25.5±4.14 years)	Cervical portion of the descending trapezius muscle (TC), lateral portion of the descending trapezius muscle (TL), infraspinatus muscle (IS)	Grasping a small cylinder with the right hand, releasing it through a hole in the table; Subject was seated with 90º of flexion in the hips and in the knees; work pace: MTM-132, 41 work cycle per minute with a cycle time of 1.22s	Repetitive work was performed: C1: without pauses during 60 min. and; C2: with 1 min. of pause every sixth min. – 50 min. of work and 10 min. of pause.	EMG RPE	EMG MPF: C1 (TL): decrease (8 subjects) (n.d.) C2 (TL): decrease (8 subjects) (n.d.) C1 (TC): decrease (8 subjects) (n.d.) C2 (TC): decrease (3 subjects) (n.d.) C1 (IS): decrease (3 subjects) (n.d.) C2 (IS): none subjects (n.d.) EMG RMS: C1 (TL): increase (8 subjects) (n.d.) C2 (TL): increase (8 subjects) (n.d.) C1 (TC): increase (8 subjects) (n.d.) C2 (TC): increase (3 subjects) (n.d.) C1 (IS): increase (3 subjects) (n.d.) C2 (IS): none subjects (n.d.)	RPE: n.s. between C1 and C2 ($p < 0.053$)

Abreviations: M, male; F, female; s, seconds; MPF, mean power frequency; RPD, rating of perceived discomfort; RPE, rating of perceived exertion; n.a., not applicable; n.d., not defined; n.s., not significant; MES, myoelectric signal; MNF, mean frequency; VAS, visual analogue scale; RMS, root mean square.

3.3.3. Effects of work pace, duty cycle and cycle time

In the seven studies reviewed (see Table 3), one analyzed only the influence of work duration (Bosch, *et al*., 2007) and three studies investigated only the effect of work pace on muscle fatigue and/or muscle activity (Gooyers & Stevenson, 2012; Bosch, *et al*., 2011; Gerard, *et al*., 2002). The remaining articles tested experimental protocols with variation of contraction level (CL), duty cycle (DC), cycle time (Iridiastadi & Nussbaum, 2006) and with variation of working time and work pace simultaneously (Mathiassen & Winkel, 1996).

Gooyers & Stevenson (2012) showed that the increase in work rate (7 fasteners per minute to 21 fasteners per minute) contributed to a significant increase in muscle activity (50^{th} percentile muscle activity) for the *extensor carpi radialis longus* (ER) and a significant increase in average integrated EMG (total muscular effort) for the ER and *biceps brachii* (BC). These results indicated that 21 fasteners per minute were more fatiguing than 7 fasteners per minute. However, only two of the six muscles examined were significantly affected by an increase in work rate. Importantly, the collection of EMG data in forearm muscles could be influenced by a phenomenon known as EMG crosstalk. This phenomenon occurs as a result of the proximity of various muscles included in the forearm and a relatively small surface area of the overlying skin to place recording electrodes (Mogk & Keir, 2003). The Bosch *et al*. (2011) study did not observe a significant effect of work pace on EMG manifestations of muscle fatigue. As expected, the distance covered by wrist and elbow (relative to wrist and to shoulder) was significantly shorter in “high” work pace (HWP). Speed and acceleration were significantly higher during the same condition. Performance was affected by work pace because participants made more errors per cycle during the HWP. Gerard, *et al*. (2002) showed that the increase in typing pace resulted in a linear increase in finger flexor and extensor EMG activity and typing force.

The field study of Bosch *et al*. (2007) was performed under realistic working conditions and no differences were found in EMG MPF and amplitude between normal (8 hours) and extended working days (9.5 hours).

Mathiassen & Winkel (1996) confirmed that daily duration might be more effective in reducing acute fatigue than reducing work pace or increasing breaks. Indeed, for 4 hours of work at a pace of 100-120 methods-time measurement system (MTM), a complete recovery of EMG variables, maximal strength, heart rate, blood pressure sensitivity, and tenderness was observed. As expected, the heart rate (HR) was higher with 120 MTM than with 100 MTM. Iridiastadi & Nussbaum (2006) found that CL and DC significantly affected endurance time and muscle fatigue. However, EMG spectral measures did not always present a typical pattern.

In the six studies analyzed, five of them evaluated perceived discomfort or fatigue. The increase in work pace negatively affected perceived fatigue or discomfort in studies performed by Gerard *et al*. (2002) and the Mathiassen & Winkel (1996). However, in the last study mentioned, the implementation of active or passive breaks did not have a significant effect on subjective ratings. Bosch *et al*. (2011) did not observe a significant difference between high and low work pace. Finally, Iridiastadi & Nussbaum (2006) demonstrated that CL and DC had a significant effect on perceived discomfort.

Table 3. Overview of results of "effects of work pace, duty cycle and cycle time".

Reference	**Sample**	**Muscle group**	**Task**	**Conditions**	**Fatigue measure**	**Response variables and main outcomes**	
						Objective Fatigue	***Subjective fatigue***
Bosch et al. (2011)	General population *N* = 8 (8F, age: 20.5±1.8 years)	Upper trapezius (Trap), deltoid anterior (Delt) and extensor digitorum (ExtD)	Simulate industrial assembly: 2-h to pick, place and remove three pins, three collars and three washers in a fixed order with the left and right hand simultaneously - sitting, knee angle of 90º, placing the table surface 5 cm below the position of the wrist when the elbow was 90ºflexed	C1: "low" work pace (LWP) - cycle time of 48 s. C2: "high" work pace (HWP) - cycle time of 38 s.	Kinematic data EMG Force transducer Performance Perceived fatigue Pressure pain threshold (PPT)	Average EMG activity levels (%MVE): C2 > C1 (Trap) (n.s.) C1 > C2 (Delt) (n.s.) C1 > C2 (ExtD) (n.s.) Average cycle-to-cycle variability (EMG amplitude and EMG MPF): n.s. between C1 and C2 (Trap. - p = 0.58 and Delt. - p = 0.48) C2 > C1 (ExtD) (p = 0.012) Distance covered (m): C1 > C2 (wrist) (p = 0.012) C1 > C2 (elbow relative to wrist) (p = 0.012) C1 > C2 (elbow relative to shoulder) (p = 0.017) Speed (cm/s): C2 (wrist) > C1 (wrist) (p = 0.012) Acceleration (mm/s^2) : C2 (wrist) > C1 (wrist) (p = 0.017) Maximum shoulder force: n.s. between C1 and C2 (p = 0.86) PPT: n.s. between C1 and C2 (Trap, Delt) (p = 0.9) Performance (errors per work cycle): C2 > C1 (p = 0.017)	Level of fatigue: n.s. between C1 and C2 (p = 0.307)

Reference	Sample	Muscle group	Task	Conditions	Fatigue measure	Response variables and main outcomes	
						Objective Fatigue	***Subjective fatigue***
Iridiastadi & Nussbaum (2006)	University population *N* = 48 (24M and 24F, age: 21.8±2.1 years)	Middle deltoid muscle	Intermittent static arm abductions: secured in a supine posture, with the right arm abducted at 90° - performed no fatiguing shoulder abductions, followed by a measurement of the individual's abduction MVE. (20-60 min.)	C1: 28%MVE (CL), 0.75 (DC), 166 s (CT) – HHH C2: 28%MVE (CL), 0.75 (DC), 34 s (CT) – HHL C3: 28%MVE (CL), 0.25 (DC), 166 s (CT) – HLH C4: 28%MVE (CL), 0.25 (DC), 34 s (CT) – HLL C5: 12%MVE (CL) , 0.75 (DC), 166 s (CT) – LHH C6: 12%MVE (CL), 0.75 (DC), 34 s (CT) – LHL C7: 12%MVE (CL), 0.25 (DC), 166 s (CT) – LLH C8: 12%MVE (CL), 0,25 (DC), 34 s (CT) – LLL	EMG RPD	Endurance Times (min.): C5-C8 > C4 > C3 > C2 > C1 (*Main and interactive effects: CL (p < 0.001); DC (p < 0.001); CL x DC (p < 0.001)*) Strength (%/min.): C8 > C5 and C7 > C6 > C3 > C4 > C1 and C2 (*Main and interactive effects: CL (p < 0.001)*) EMG RMS (%/min.): C1> C2 > C8 > C3 and C4 > C6 and C7 > C5 (n.s) EMG MPF(%/min.): C7 > C4 and C6 > C3 > C8 > C5 > C2 > C1 (*Main and interactive effects: CL (p < 0.001); DC (p < 0.001); CT (p = 0.029); CL x DC (p = 0.033)*) EMG MF(%/min.): C8 > C4 > C3 and C6 > C7 > C5 > C2 > C1 (*Main and interactive effects: CL (p = 0.004); DC (p < 0.001); CT (p = 0.006); CL x DC (p = 0.003)*)	RPD: C1 > C2 > C4 > C3 > C5 > C6 > C8 and C7 (*Main and interactive effects: CL (p < 0.001); DC (p = 0.002)*)
Mathiassen & Winkel (1996)	General population N = 8 (8F, age: 22-32 years)	Right upper trapezius muscle	Assembling starters for power saws: components (six parts and five screws) weighed up to 90 g and the complete starter 220 g.	C1: 2 h of work at 120 MTM C2: 4 h of work at 120 MTM C3: 6 h of work at 120 MTM C4: 4 h of work at 100 MTM C5: 6 h of work at 100 MTM C6: 4 h of work at 120 MTM with 20 min. of active breaks C7: 4 h of work at 120 MTM with 20 min. of passive breaks	EMG Heart rate (HR) Pressure pain threshold (PPT) Perceived fatigue	EMG APDF (%RVE) : Higher at 120 MTM than 100 MTM (interaction of pace and hour: *p* = 0.03 at 10th percentile level and *p* = 0.06 at 50th percentile level). EMG EVA: Higher at 120 MTM than 100 MTM (interaction of pace and hour: *p* = 0.09). HR: Higher at 120 MTM than 100 MTM (n.d.) n.s. between C6 and C7 (n.d.) PPT: Higher at 120 MTM than 100 MTM (only for the first 4 h of work) (n.d.)	Perceived fatigue: Higher at 120 MTM than 100 MTM (n.d.) No conclusive effects for C6 and C7

Reference	Sample	Muscle group	Task	Conditions	Fatigue measure	Response variables and main outcomes	
						Objective Fatigue	***Subjective fatigue***
Gerard et al. (2002)	Typists N = 18 (16F and 2M, age: 34±10 years)	Flexor digitorum superficialis and extensor digitorum communis.	Typing for three 30 min. trials.	C1: self-pace; C2: 50% of the participant's 1-min. maximum typing speed; C3: 100% of the participant's1-min. maximum typing speed	EMG Force Subjective discomfort	Typing speed (WPM): C3 > C1 > C2 (n.d.) Typing force (10th, 50th and 90th APDF percentiles): C3 and C1 > C2 ($p < 0.01$) EMG (50th APDF percentile): C3 > C1 > C2 ($p < 0.01$) (finger flexor) EMG (90th APDF percentile): C1 > C2 ($p < 0.01$) (finger flexor) C3 > C1 and C2 ($p < 0.01$) (finger flexor) EMG (10th, 50th and 90th APDF percentiles): C1 > C2 ($p < 0.01$) (finger extensor) C3 > C1 and C2 ($p < 0.05$) (finger extensor)	Subjective discomfort: C3 > C1 and C2 ($p < 0.01$) (fingers) C3 > C1 and C2 ($p < 0.01$) (lower arm) C3 > C1 and C2 ($p < 0.01$) (overall task)
Gooyers & Stevenson (2012)	Students *N* = 12 (12F, age: 23.6±1.8 years)	Flexor carpi radialis (FR), extensor carpi radialis longus (ER), biceps brachii (BC), triceps brachii (TC), anterior deltoid (AD), and the upper trapezius (UT).	Simulated Speed Fastening (SF) task - using a pneumatic, powered, pistol-grip hand tool, to broach a 4.76 mm stainless-steel fastener at waist and shoulder height into perforated Masonite pegboard (hole diameter = 6.35 mm). (120 min at a 50% work-to-rest duty cycle)	C1: 7 fasteners per minute C2: 14 fasteners per minute C3: 21 fasteners per minute	EMG Kinematic data	50th muscle activity (%MVC): C3 > C2 (ER) ($p < 0.0001$; 3%MVC) C3 > C1 (ER) ($p < 0.0001$; 7%MVC) C3 > C1 (BC) ($p < 0.0573$; 2%MVC) Integrate EMG muscle activity (total muscular effort): C3 > C1 (ER) ($p = 0.0019$) C3 > C1 (BC) ($p = 0.0122$) 50th upper extremity joint posture: n.s. effect of work pace	n.a.

Reference	Sample	Muscle group	Task	Conditions	Fatigue measure	Responses variables and main outcomes	
						Objective Fatigue	***Subjective fatigue***
Bosch et al. (2007)	Case study 1 Assemblers *N* = 10 (4 M and 6 F, age: 38.5±8.0)	Upper trapezius (muscle	Assembly of catheters by picking and placing small parts.	C1: 8 h per working day for a period of 4 weeks (normal days) C*2:* 9.5 h per working day for a period of 4 weeks (extended days).	EMG RPD	EMG MPF: n.s. between C1 and C2 ($p = 0.211$) EMG amplitude: n.s. between C1 and C2 ($p = 0.203$)	RPD: C2 > C1 ($p = 0.019$)

Abreviations: M, male; F, female; MVC, maximum voluntary contraction; MVE, maximum voluntary electrical activity; MPF, mean power frequency; MF, median power frequency; RPD, rating of perceived discomfort; n.a., not applicable; n.d., not defined; n.s., not significant; RMS, root mean square; WPM, words per minute; RVE, sub-maximal reference contraction; EVA, exposure variation analysis; MTM, methods-time measurement.

3.3.4. Quality assessment

Table 4 shows the methodological quality assessment of the included studies. The scores on the methodological quality assessment ranged from 4 to 8 (on a scale from 0 to 8). Two studies (Bosch, *et al*., 2011; Wells, *et al*., 2010) met the assessment criteria in full. However, the criteria related to study design, variables, data sources/measurement as well as outcome data were fulfilled for all studies included in this review. Nine studies did not define clearly the eligibility criteria and methods of selection of participants (Horton, *et al*., 2012; Keir, *et al*., 2011; Raina & Dickerson, 2009; Bosch, *et al*., 2007; Balci & Aghazadeh, 2004; Gerard *et al*., 2002; Christensen, *et al*., 2000; Mathiassen & Winkel, 1996; Sundelin, 1993). Though, all studies included reported that participants did not have history of musculoskeletal injury. Regarding the criteria defined to item bias, three studies did not refer any effort to address bias or imprecision (Raina & Dickerson, 2009; Balci & Aghazadeh, 2004; Gerard, *et al*., 2002) and two did not describe clearly the measures to minimize it (Bosch, *et al*., 2007; Christensen, *et al*., 2000). Additionally, only six studies discussed the external validity of the results (Horton, *et al*., 2012; Bosch, *et al*., 2011; Keir, *et al*., 2011; Wells, *et al*., 2010; Raina & Dickerson, 2009; Bosch, *et al*., 2007).

Table 4. Methodological quality scores of the included articles.

Reference	**Study design**	**Participants**	**Variables**	**Data sources/ measurement**	**Bias**	**Outcom e data**	**Limitations**	**Generalizability**	***Score (study)***
Horton, et al. (2012)	+	-	+	+	+	+	+	+	7
Keir, et al. (2011)	+	-	+	+	+	+	+	+	7
Wells, et al. (2010)	+	+	+	+	+	+	+	+	8
Raina & Dickerson (2009)	+	-	+	+	-	+	+	+	7
Balci & Aghazadeh (2004)	+	-	+	+	-	+	-	-	4
McLean et al. (2001)	+	+	+	+	+	+	+	?	7
Christensen et al. (2000)	+	-	+	+	?	+	+	?	5
Sundelin (1993)	+	-	+	+	+	+	-	-	5
Bosch et al. (2011)	+	+	+	+	+	+	+	+	8
Bosch et al. (2007)	+	-	+	+	?	+	+	+	6
Gooyers & Stevenson	+	+	+	+	+	+	+	?	7

Reference	Study design	Participants	Variables	Data sources/ measurement	Bias	Outcome data	Limitations	Generalizability	*Score (study)*
(2012)									
Iridiastadi & Nussbaum (2006)	+	+	+	+	+	+	+	?	7
Gerard et al. (2002)	+	-	+	+	-	+	-	?	4
Mathiassen & Winkel (1996)	+	-	+	+	+	+	+	?	6
Score (item)	14	5	14	14	9	14	11	6	

The analysis of the methodological quality revealed that, in general, the included laboratory studies, investigated young small samples in contrast with field studies or studies with samples of workers. Considering that some authors found age differences in responses to fatiguing tasks (Adamo, Khodaee, Barringer, Johnson, & Martin, 2009; Avin & Law, 2011), these factors could limit generalization of the outcomes to older workers. Only three studies (Bosch, *et al*., 2007; Christensen, *et al*., 2000; Mathiassen & Winkel, 1996) performed their evaluations in specific moments of a full workday or longer periods of work. So, other critical factor of the experimental protocol tested in the laboratory studies was the representativeness of the period of trials. Thus, the results may not be representative of fatigue experienced by workers in real-occupational settings. Only one study obtained EMG signals exclusively during a pre-defined test contraction (Bosch, *et al*., 2007) and three studies compared EMG measures from work period and reference test contraction (Horton, *et al*., 2012; Christensen, *et al*., 2000; Mathiassen & Winkel, 1996). These two methods can be applied to EMG evaluation of fatigue yet the results can be analyzed considering some constraints. Under dynamic conditions, EMG is no stationary and some confounding factors are difficult to control such as modifications in force output, muscle length, position and distance of electrodes, as well as movement velocity during the task (Farina, 2006; Madeleine, Bajaj, Søgaard, & Arendt-Nielsen, 2001). EMG analysis of muscle groups with highly dynamic movements in manual tasks, such as wrist flexors and extensors, these factors are more uncontrolled and may lead to interpretation errors of the EMG signals. However, test contraction method has also disadvantages, since may not represent accurately the workload and motor unit recruitment during real work tasks.

3.4. Conclusions and future research

In general, the articles analyzed in this systematic review demonstrated that the influence of task design on muscle fatigue and performance are not completely understood. The studies reviewed did not demonstrate a significant effect of job rotation on perceived discomfort and objective EMG indicators of fatigue. In these studies the duration of trials and number of participants appears to be the factors which have the most influence on the results. However, Srinivasan & Mathiassen (2012) proposed an alternative intervention to job rotation, based on variation in postures, movements and muscle activity during the performance of tasks - motor variability – on muscle fatigue.

Regarding the studies which analyzed the temporal aspects of work on muscle fatigue, it was found that the introduction of breaks had a positive effect on subjective feelings in the office work studies. However, no clear relationship was found between perceived discomfort and objective measurements of fatigue. Overall, an increase of work pace resulted in higher manifestation of muscle fatigue in the EMG signal (higher amplitude and lower frequency). In these studies the demographic characteristics, in particular, age and experience in the tasks may have influenced the results.

Therefore, future studies should extent the period of experiments to be more representative of fatigue in real work conditions. In addition, it is crucial to study the effects of temporal aspects of work and rotation schemes in specific populations such as older workers. Recognizing the limitations of surface EMG to detect fatigue at low-load work, future research should be focused on the improvement of instrumentation for data collection and analysis in occupational settings. These advances will allow detect the causes of muscle fatigue and prevent its development in the workplaces.

Some limitations were present in this review that should be noted. This review only included research published in English peer-reviewed journals, not including potential relevant studies in other languages. Additionally, the electronic search was limited to three databases.

3.5. References

Adamo, D. E., Khodaee, M., Barringer, S., Johnson, P. W., & Martin, B. J. (2009). Low mean level sustained and intermittent grip exertions: influence of age on fatigue and recovery. *Ergonomics*, *52*(10), 1287–1297.

Aptel, M., Cail, F., Gerling, A., & Louis, O. (2008). Proposal of parameters to implement a workstation rotation system to protect against MSDs. *International Journal of Industrial Ergonomics*, *38*(11-12), 900–909. doi:10.1016/j.ergon.2008.02.006

Avin, K. G., & Law, L. A. F. (2011). Age-related differences in muscle fatigue vary by contraction type: a meta-analysis. *Physical Therapy*, *91*(8), 1153–1165.

Balci, R., & Aghazadeh, F. (2004). Effects of exercise breaks on performance, muscular load, and perceived discomfort in data entry and cognitive tasks. *Computers & Industrial Engineering, 46*(3), 399-411.

Blangsted, A. K., Sjøgaard, G., Madeleine, P., Olsen, H. B., & Søgaard, K. (2005). Voluntary low-force contraction elicits prolonged low-frequency fatigue and changes in surface electromyography and mechanomyography. *Journal of Electromyography and Kinesiology, 15*(2), 138-148.

Bosch, T., De Looze, M. P., & Van Dieen, J. H. (2007). Development of fatigue and discomfort in the upper trapezius muscle during light manual work. *Ergonomics, 50*(2), 161-177.

Bosch, T., Mathiassen, S. E., Visser, B., de Looze, M. P., & van Dieen, J. H. (2011). The effect of work pace on workload, motor variability and fatigue during simulated light assembly work. *Ergonomics, 54*(2), 154-168.

Christensen, H., Sogaard, K., Pilegaard, M., & Engineer, H. B. O. (2000). The importance of the work/rest pattern as a risk factor in repetitive monotonous work. *International Journal of Industrial Ergonomics, 25*(4), 367-373.

Dababneh, A. J., Swanson, N., & Shell, R. L. (2001). Impact of added rest breaks on the productivity and well being of workers. *Ergonomics, 44*(2), 164-174.

Ding, J., Wexler, A. S., & Binder-Macleod, S. A. (2000). A predictive model of fatigue in human skeletal muscles. *Journal of Applied Physiology, 89*(4), 1322-1332.

Eurofound. (2010). Changes over time - First findings from the fifth European Working Conditions Survey. Dublin.

Enoka, R. M., & Duchateau, J. (2008). Muscle fatigue: what, why and how it influences muscle function. *Journal of Physiology, 586*(1), 11-23.

Fallentin, N., Viikari-Juntura, E., Wærsted, M., & Kilbom, Å. (2001). Evaluation of physical workload standards and guidelines from a Nordic perspective. *Scandinavian Journal of Work, Environment and Health*, *27*, 1–52.

Farina, D. (2006). Interpretation of the surface electromyogram in dynamic contractions. *Exercise and Sport Sciences Reviews*, *34*(3), 121-127.

Fuller, J. R., Lomond, K. V., Fung, J., & Cote, J. N. (2009). Posture-movement changes following repetitive motion-induced shoulder muscle fatigue. *Journal of Electromyography and Kinesiololy, 19*(6), 1043-1052.

Gerard, M. J., Armstrong, T. J., Martin, B. J., & Rempel, D. A. (2002). The effects of work pace on within-participant and between-participant keying force, electromyography, and fatigue. *Human Factors, 44*(1), 51-61.

Gooyers, C. E., & Stevenson, J. M. (2012). The impact of an increase in work rate on task demands for a simulated industrial hand tool assembly task. *International Journal of Industrial Ergonomics, 42*(1), 80-89.

Greenhalgh, T., Robert, G., Bate, P., Macfarlane, F., & Kyriakidou, O. (2005). Diffusion of Innovations in Health Service Organisations: A Systematic Literature Review. Oxford: Blackwell Publishing Ltd. doi:10.1002/9780470987407

Hansson, G. A., Balogh, I., Ohlsson, K., Palsson, B., Rylander, L., & Skerfving, S. (2000). Impact of physical exposure on neck and upper limb disorders in female workers. *Applied Ergonomics, 31*(3), 301-310.

Horton, L. M., Nussbaum, M. A., & Agnew, M. J. (2012). Effects of rotation frequency and task order on localised muscle fatigue and performance during repetitive static shoulder exertions. *Ergonomics, 55*(10), 1205-1217.

Iridiastadi, H., & Nussbaum, M. A. (2006). Muscular fatigue and endurance during intermittent static efforts: Effects of contraction level, duty cycle, and cycle time. *Human Factors, 48*(4), 710-720.

Keir, P. J., Sanei, K., & Holmes, M. W. R. (2011). Task rotation effects on upper extremity and back muscle activity. *Applied Ergonomics, 42*(6), 814-819.

Kilbom, Å. (1994). Repetitive work of the upper extremity: Part I—Guidelines for the practitioner. *International Journal of Industrial Ergonomics, 14*(1–2), 51-57.

Lomond, K. V., & Cote, J. N. (2011). Shoulder functional assessments in persons with chronic neck/shoulder pain and healthy subjects: Reliability and effects of movement repetition. *Work: a Journal of Prevention Assessment & Rehabilitation, 38*(2), 169-180.

Madeleine, P., Bajaj, P., Søgaard, K., & Arendt-Nielsen, L. (2001). Mechanomyography and electromyography force relationships during concentric, isometric and eccentric contractions. *Journal of Electromyography and Kinesiology*, *11*(2), 113–121.

Mathiassen, S. E. (2006). Diversity and variation in biomechanical exposure: what is it, and why would we like to know? *Applied Ergonomics, 37*(4), 419-427.

Mathiassen, S. E., & Winkel, J. (1996). Physiological comparison of three interventions in light assembly work: Reduced work pace, increased break allowance and shortened working days. *International Archives of Occupational and Environmental Health, 68*(2), 94-108.

McLean, L., Tingley, M., Scott, R. N., & Rickards, J. (2000). Myoelectric signal measurement during prolonged computer terminal work. *Journal of Electromyography and Kinesiololy, 10*(1), 33-45.

McLean, L., Tingley, M., Scott, R. N., & Rickards, J. (2001). Computer terminal work and the benefit of microbreaks. *Applied Ergonomics, 32*(3), 225-237.

Mogk, J. P., & Keir, P. J. (2003). Crosstalk in surface electromyography of the proximal forearm during gripping tasks. *Journal of Electromyography and Kinesiololy, 13*(1), 63-71.

Muggleton, J. M., Allen, R., & Chappell, P. H. (1999). Hand and arm injuries associated with repetitive manual work in industry: a review of disorders, risk factors and preventive measures. *Ergonomics, 42*(5), 714-739.

Neumann, W. P., Kihlberg, S., Medbo, P., Mathiassen, S. E., & Winkel, J. (2002). A case study evaluating the ergonomic and productivity impacts of partial automation strategies in the electronics industry. *International Journal of Production Research, 40*(16), 4059-4075.

Nussbaum, M. A., Clark, L. L., Lanza, M. A., & Rice, K. M. (2001). Fatigue and endurance limits during intermittent overhead work. *American Industrial Hygiene Association Journal*, *62*(4), 446-456.

Raina, S. M., & Dickerson, C. R. (2009). The influence of job rotation and task order on muscle fatigue: A deltoid example. *Work: a Journal of Prevention Assessment & Rehabilitation, 34*(2), 205-213.

Srinivasan, D., & Mathiassen, S. E. (2012). Motor variability in occupational health and performance. *Clinical Biomechanics*, *27*(10), 979-993.

Sundelin, G. (1993). Patterns of electromyographic shoulder muscle fatigue during MTM-paced repetitive arm work with and without pauses. *International Archives of Occupational and Environmental Health, 64*(7), 485-493.

Thomsen, J. F., Hansson, G. A., Mikkelsen, S., & Lauritzen, M. (2002). Carpal tunnel syndrome in repetitive work: a follow-up study. *American Journal of Industrial Medicine, 42*(4), 344-353.

van den Heuvel, S. G., de Looze, M. P., Hildebrandt, V. H., & Thé, K. H. (2003). Effects of software programs stimulating regular breaks and exercises on work-related neck and upper-limb disorders. *Scandinavian Journal of Work, Environment and Health, 29*(2), 106-116.

van der Windt, D. A., Thomas, E., Pope, D. P., de Winter, A. F., Macfarlane, G. J., Bouter, L. M., & Silman, A. J. (2000). Occupational risk factors for shoulder pain: a systematic review. *Occupational and Environmental Medicine, 57*(7), 433-442.

Viikari-Juntura, E., & Silverstein, B. (1999). Role of physical load factors in carpal tunnel syndrome. *Scand J Work Environ Health, 25*(3), 163-185.

Vollestad, N. K. (1997). Measurement of human muscle fatigue. *Journal of Neuroscience Methods, 74*(2), 219-227.

Von Elm, E., Altman, D. G., Egger, M., Pocock, S. J., Gøtzsche, P. C., & Vandenbroucke, J. P. (2008). The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. *Journal of Clinical Epidemiology*, *61*(4), 344–349.

Wells, R., Mathiassen, S. E., Medbo, L., & Winkel, J. (2007). Time--a key issue for musculoskeletal health and manufacturing. *Applied Ergonomics, 38*(6), 733-744.

Wells, R., McFall, K., & Dickerson, C. R. (2010). Task selection for increased mechanical exposure variation: Relevance to job rotation. *Ergonomics, 53*(3), 314-323.

Willliams, C., Ratel, S. (Ed.). (2009). *Human Muscle Fatigue*. Abingdon, Oxon: Routlegde.

Yung, M., Mathiassen, S. E., & Wells, R. P. (2012). Variation of force amplitude and its effects on local fatigue. *European Journal of Applied Physiology, 112*(11), 3865-3879.

CHAPTER 4: Portuguese version of the Swedish Occupational Fatigue Inventory (SOFI) among industrial workers: cultural adaptation, reliability and validity

Abstract

Reliable and valid instruments are essential for understanding fatigue in occupational settings. This study analyzed the psychometric properties of the Portuguese version of the Swedish Occupational Fatigue Inventory (SOFI). A cross-sectional study was conducted with 218 workers from an automotive industry involved in assembly tasks for fabrication of mechanical cables. Convergent and discriminant validity, internal consistency reliability and confirmatory factor analysis were performed. Results showed an adequate fit to data, yielding a 20-item, five-factor structure (all intercorrelated): χ^2/df = 2.530, CFI = 0.919, GFI = 0.845, RMSEA = 0.084. The SOFI presented an adequate internal consistency, with the sub-scales and total scale presenting good reliability values (Cronbach's Alpha values from 0.742 to 0.903 and 0.943 respectively). Findings suggest that the Portuguese version of SOFI can be a useful tool to assess fatigue and prevent work related injuries.

Keywords: Perceived fatigue; validity; reliability; Swedish occupational fatigue inventory.

4.1. Introduction

The term fatigue has been used consistently in the literature to describe a state of tiredness that is clinically significant and pathological in nature (Jorgensen, 2008). It is usually defined as a condition of feeling very tired, weary or sleepy resulting from insufficient sleep, prolonged mental or physical work, extended periods of stress or anxiety. However, recently, a new whole definition of fatigue was proposed by Phillips (2015, 53), "*Fatigue is a suboptimal psychophysiological condition caused by exertion. The degree and dimensional character of the condition depends on the form, dynamics and context of exertion. The context of exertion is described by the value and meaning of performance to the individual; rest and sleep history; circadian effects; psychosocial factors spanning work and home life; individual traits; diet; health, fitness and other individual states; and environmental conditions. The fatigue condition results in changes in strategies or resource use such that original levels of mental processing or physical activity are maintained or reduced.*"

Fatigue is probably the most common symptom of illness affecting sufferers of both acute and chronic conditions (Ream & Richardson, 1996). It results from the interaction between mental and physical factors, which are very difficult to evaluate separately (Saito, 1999), and it is usually associated with boring or repetitive work-related tasks. At the broadest level, occupational fatigue has been linked to an imbalance between the intensity and duration and timing of work with recovery time (Dawson, Ian Noy, Härmä, Kerstedt, & Belenky, 2011). Indeed, acute fatigue can occur when there is inadequate time to rest and recover from a work period. It tend to disappear after taking some rest (Janssen & Nijhuis, 2004). On the other hand, cumulative (chronic) fatigue occurs when there is insufficient recovery from acute fatigue over time (Gander et al., 2011).

Fatigued workers may find themselves working closer to their maximal capabilities, putting themselves at greater risk for the development of not only musculoskeletal injuries, but also psychosocial disorders (Kenny, Yardley, Martineau, & Jay, 2008). Several studies have identified that fatigue is a contributing factor for accidents, injuries and death in a wide range of settings, because people with fatigue symptoms are less likely to produce safe performance and actions (Williamson et al. 2011; Dinges 1995). Consequently, in order to avoid chronic fatigue, it is important to develop effective strategies or measures to prevent (Bültmann, Kant, van Amelsvoort, van den Brandt, & Kasl, 2001) and detect acute fatigue and to recover from it (Mizuno, Tajima, Watanabe, & Kuratsune, 2014; Tanaka, Yamada, Nakamura, & Watanabe, 2012). In general, fatigue is not well understood and it is typically measured as a multidimensional phenomenon with subjective and performance based indicators. The objective measures of fatigue are largely related to its physiological parameters, while subjective indicators report self-perceived feelings (Leung, Chan, & He, 2004). Within occupational settings, the need to minimize assessment time and to maximize compliance by ensuring that measures are simple, easy and valid for the work, influences the selection of which measures are used and the measurement regime (Williamson, Friswell, and Feyer 2004). Assessing perceived fatigue (measured through the use of self-report measures) seems to be adequate to measure fatigue. There are several instruments developed to assess fatigue for clinical use, and a few for occupational context. The Swedish Occupational Fatigue Inventory (SOFI) (Åhsberg, 2000), is an example of a self-report instrument developed for occupational assessment of fatigue, which has been used in both contexts, over the last fifteen years (Gershon, Shinar, & Ronen 2009;

Hagelin et al. 2009; Johansson et al. 2008; Karlson et al. 2006; Krupinski & Berbaum 2010; Leung et al. 2006; Muller, Carter, & Williamson 2008; Persson et al. 2003; Åhsberg & Fürst 2001). Considering that there is no Portuguese version of SOFI, the aim of this study is to present the translation and cultural adaptation process of the SOFI into European Portuguese and to examine the psychometric properties of the Portuguese version among industrial workers.

4.2. Materials and Methods

4.2.1. Sample

A cross-sectional study was conducted at a multinational corporation devoted to the production of mechanical cables for the automotive industry. The Portuguese version of SOFI was applied to 290 workers of the production section at the end of their shifts. Each of them received an instruction sheet, a demographic form, the SOFI as well as the consent form. Two hundred and eighteen workers delivered the SOFI fulfilled (response rate of 75.17%). The company works 24 h a day and working hours are distributed over three shifts (morning shift: 6 a.m. to 2 p.m.; afternoon shift: 2 p.m. to 10 p.m.; night shift: 10 p.m. to 6 a.m.). The dominant gender of the sample was female (92.70%). The average age was 36.20±9.37 years (18 the youngest and 61 the oldest). The shift distribution was 56.80% (afternoon shift), 23.00% (morning shift) and 20.10% (night shift). The company direction board approved this study, and all participants gave their written informed consent.

4.2.2. Instrument

The initial version of SOFI consisted of 25 expressions which represented five dimensions/sub-scales: lack of energy; physical exertion; physical discomfort; lack of motivation, and sleepiness (Åhsberg, Gamberale, & Kjellberg 1997). Each dimension was defined by the content of five expressions, related to physiological, cognitive, motor and emotional responses (González Gutiérrez, Jiménez, Hernández, & López, 2005). An l1-grade response scale was used, where only the two extreme values had a verbal label, 0 "not at all" and 10 "to a very high degree" (Åhsberg, Gamberale, & Kjellberg 1997). However, after testing the validity of all the dimensions of SOFI (Åhsberg, Gamberale, & Kjellberg 1997; Åhsberg & Gamberale 1998; Åhsberg, Gamberale, &

Gustafsson 2000; Åhsberg et al. 2000), the final version maintained the five dimensions but with 20 expressions. The internal consistency for each factor of this version varied between 0.81-0.92. During this process, the 11-grade response scale was replaced by a 7-grade response scale, where the extreme values were verbally labeled, 0 "not at all" and 6 "to a very high degree" (Åhsberg, 2000). SOFI (Åhsberg, 2000) was already translated and validated into Spanish and Chinese languages (González Gutiérrez et al., 2005; Leung et al., 2004), with good psychometric characteristics.

4.2.3. Translation and cultural adaptation process

This process was carried out according to the guidelines of the International Society for Pharmacoeconomics and Outcomes Research (ISPOR) (Wild et al., 2005), beginning with permission to use the SOFI to the main author of the instrument. Two authors of this research, who are fluent in English, and an English translator, made forward translation from English into Portuguese. At this stage, the clarification of some expressions was discussed with the original instrument's author. After the forward translations had been analyzed, a single forward translation was achieved. Two professional English translators carried out the back translation. The back translation results were reviewed, and a harmonization of all new versions and source version was performed in order to detect and deal with any discrepancies that could have arisen between different language versions, ensuring conceptual equivalence (Coelho, Santos, Paul, Gobbens, & Fernandes, 2014; Wild et al., 2005). To assess the level of comprehensibility of the translation, a cognitive debriefing was made, involving a pretest with twenty-two participants. In addition, a multidisciplinary panel (three experts regarding psychology, ergonomics and occupational health research) was asked to proofread and to provide their opinion and on the face and content validity of the preliminary version. Although the draft was shown to be acceptable in the preliminary pilot survey, slightly changes were made to the original expressions (details are given in Appendix C).

4.2.4. Data Analysis

Descriptive techniques were used to analyze and characterize the subjects. Confirmatory factor analysis (CFA) of the Portuguese version to verify the five-dimensional structure proposed by Åhsberg (2000) was carried out. In this sense the following goodness of fit indices were used: ratio chi-square and degrees of freedom (χ^2/df), confirmatory fit index (CFI), Tucker Lewis index (TLI), goodness of fit index (GFI), Parsimony Goodness-of-Fit Index (PGFI) and root mean square error of approximation (RMSEA). The model's adjustment was considered good for CFI, GFI and TLI values above 0.90, RMSEA values between 0.06 and 0.10, and PGFI values above 0.60 (Marôco, 2010). To examine whether each dimension of the observed variables were strongly related to each other, the convergent validity was evaluated. The Average Variance Extracted (AVE) and the Composite Reliability (CR) were estimated (Fornell & Larcker, 1981; Marôco, 2010). Values of AVE > 0.50 and CR > 0.70 are indicative of convergent validity and adequate construct reliability (Marôco, 2010). Whether the items that reflect a dimension are not correlated with another dimension, i.e., if the AVE for each dimension is greater than the average variation shared between each factor and other factors in the model is determined by the assessment of discriminant validity (Marôco, 2010). The discriminant validity was estimated according to Fornell & Larcker (1981) proposal who claim that for two factors *i* and *j*, if AVE_i and $AVE_j > \rho_{ij}^2$ (ρ_{ij}^2: squared correlation between factors *i* and *j*), an evidence of discriminant validity exists. Factorial validity was assessed by the analysis of factorial weights of the items (λ). If all the items of a dimension have $\lambda \geq 0.5$, it is assumed that the dimension has factorial validity. If $\lambda^2 \geq 0.25$ is an indicator of an appropriate individual reliability of the item (Marôco, 2010). Internal consistency of each dimension and for total scale were estimated through Cronbach's Alpha (α). Alpha values of 0.70-0.95 were regarded as satisfactory (Terwee et al., 2007). Analysis was performed using the AMOS® version 22.0 software integrated with IBM SPSS™ Version 22.0 (SPSS Inc., Chicago, Illinois, USA), at a significance level of 5%.

4.3. Results

In a first step, the nested model proposed by Åhsberg (2000) was tested. In general the results indicated a poor fit to the data. RMSEA was above 0.10, CFI, GFI and TLI were lower than 0.90, which indicates an unacceptable adjustment to the model (Table 5).

In a second step, a model with the same 20 observed variables but evenly distributed on five latent variables (all assumed to be intercorrelated) was tested. The results shown in Table 5, revealed that this model was better compared to the nested model.

Therefore, the modification indices (MI) were inspected. They showed high error covariances between the error terms of item 12 and item 20 (MI=19.944) and also between the error terms of item 14 and item 16 (MI=24.430). The proposed final model includes the correlation between those errors as shown in Figure 8. An improvement in most of the goodness-of-fit statistics and an overall good model fit: $\chi^2/df = 2.530$, CFI = 0.919, GFI = 0.845, RMSEA = 0.084 were found. Table 5 summarizes the results from confirmatory analyses of the SOFI models tested.

The reported fatigue during work is presented in Table 6, by means, standard deviations and kurtosis indices of each item of the SOFI. *Lack of Energy* was the sub-scale which items had the highest scores, followed by *Physical Discomfort*, *Physical Exertion*, *Lack of Motivation* and *Sleepiness*.

Table 5. Summary of results from confirmatory analysis.

Model	χ^2/df	RMSEA	CFI	TLI	GFI	PGFI
Nested model 20 items	3.258	0.102	0.867	0.848	0.792	0.626
20 items	2.626	0.087	0.909	0.890	0.833	0.626
20 items (final model)	2.530	0.084	0.919	0.901	0.845	0.623

Table 6. Means (m), standard deviation (sd) and kurtosis (kurt) for ratings of fatigue on the Portuguese version of SOFI.

Sub-scale	Item	m	sd	kurt
Lack of energy	Worn out	2.54	1.810	-0.787
	Spent	2.91	1.996	-1.208
	Drained	3.15	1.950	-1.115
	Overworked	2.69	1.978	-1.168
Physical exertion	Palpitations	1.81	1.685	-0.767
	Sweaty	3.12	2.110	-1.253
	Out of breath	0.95	1.446	2.714
	Breathing heavily	1.56	1.688	0.220
Physical discomfort	Tense muscles	2.91	1.948	-1.136
	Numbness	2.02	2.007	-0.873
	Stiff Joints	2.33	2.003	-1.012
	Aching	2.58	1.993	-1.197
Lack of motivation	Lack of concern	1.39	1.519	-0.215
	Passive	1.47	1.650	0.384
	Indifferent	1.14	1.639	1.343
	Uninterested	0.92	1.484	3.026
Sleepiness	Falling asleep	1.66	1.864	-0.229
	Drowsy	1.51	1.620	0.850
	Yawning	1.62	1.595	0.373
	Sleepy	1.73	1.741	-0.149

Correlations between factors are shown in Figure 8. The values were high and varied between 0.62-0.92. Table 7 show factor weights (λ>0.50) and adequate individual reliability (λ^2>0.25) for all items. Factor weights of the items ranged between 0.601-0.770 for *Physical Exertion*, 0.692-0.853 for *Physical Discomfort*, 0.606-0.810 for *Lack of Motivation*, 0.776-0.902 for *Lack of Energy* and 0.634-0.818 for *Sleepiness*.

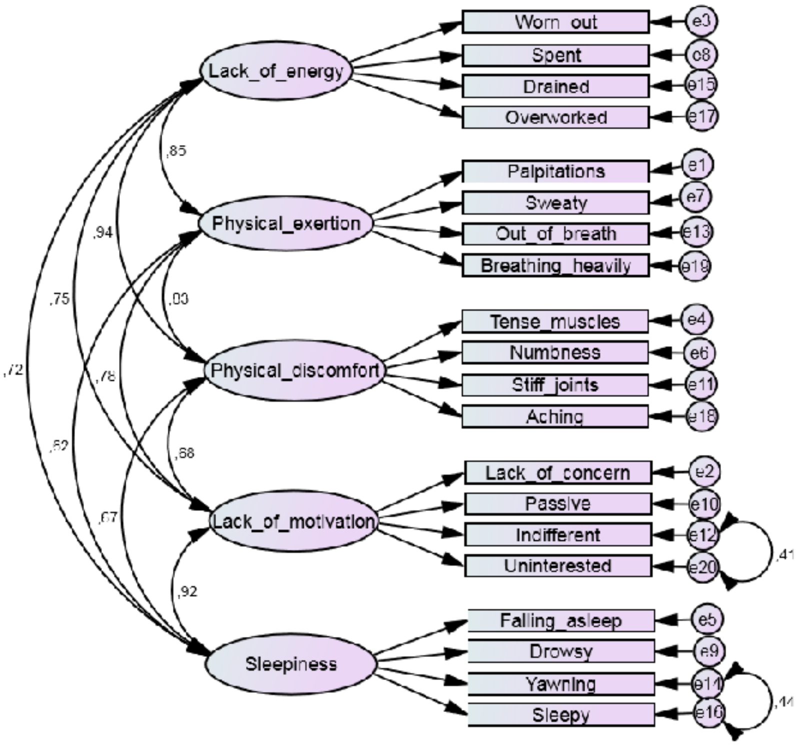


Figure 8. Confirmatory factor analysis of the Portuguese version of SOFI.

Table 7. Factorial weights (λ) of the items distributed by sub-scale.

Item	Sub-scale	λ	λ^2
Palpitations	Physical exertion	0.601	0.361
Sweaty		0.613	0.376
Out of breath		0.635	0.403
Breathing heavily		0.770	0.593
Tense muscles	Physical Discomfort	0.834	0.696
Numbness		0.692	0.479
Stiff joints		0.750	0.563
Aching		0.853	0.728
Lack of concern	Lack of Motivation	0.648	0.420
Passive		0.810	0.656
Indifferent		0.606	0.367
Uninterested		0.679	0.461
Worn out	Lack of energy	0.800	0.640
Spent		0.902	0.814
Drained		0.871	0.759
Overworked		0.776	0.602
Falling asleep	Sleepiness	0.758	0.575
Drowsy		0.818	0.669
Yawning		0634	0.402
Sleepy		0.769	0.591

The results obtained regarding internal consistency, convergent and discriminant validity are shown in Table 8. Convergent validity (AVE > 0.50 and CR > 0.7 in all dimensions, respectively), discriminant validity (ρ^2 < AVE in all dimensions) and internal consistency (α > 0.7 in all dimensions) were found to be adequate. AVE values ranged between 1.25 (*Physical Exertion*) to 4.32 (*Lack of Energy*) showing that the items of a dimension converged well with each other. CR values ranged between 0.832 (*Physical Exertion*) to 0.945 (*Lack of Energy*) and Cronbach's alpha values ranged from a high of 0.903 (*Lack of Energy*) to a low of 0.742 (*Physical Exertion*), indicating satisfactory internal consistency for all dimensions. Cronbach's alpha for the total scale of the Portuguese version of SOFI was also high (0.943).

Table 8. Average variance extracted (AVE), composite reliability (CR), Cronbach's alpha (α) and squared correlation between factors (ρ^2).

Sub-Scale	**AVE**	**CR**	**α**	ρ^2				
				Physical Exertion	Physical Discomfort	Lack of Motivation	Lack of Energy	Sleepiness
Physical Exertion	1.25	0.832	0.742	1	---	---	---	---
Physical Discomfort	2.83	0.918	0.868	0.684	1	---	---	---
Lack of Motivation	1.51	0.857	0.817	0.608	0.457	1	---	---
Lack of Energy	4.32	0.945	0.903	0.719	0.882	0.556	1	---
Sleepiness	2.19	0.897	0.848	0.383	0.449	0.852	0.514	1
Total Scale	---	---	0.943	---	---	---	---	---

4.4. Discussion

The main purpose of this study was to examine the psychometric properties of a Portuguese version of SOFI on a sample of assembly workers. Highly repetitive movements, standardized and short-cycle tasks with different levels of complexity, typically characterize assembly production systems. SOFI has been used to assess perceived fatigue in repetitive work by other researchers (Mathiassen, Hallman, Lyskov, & Hygge, 2014; Persson et al., 2003). Physical and mental aspects of fatigue assessed by SOFI are included in the recent ''whole definition'' of fatigue proposed by Phillips (2015).

Overall, the results provide preliminary evidence that the adapted version of SOFI is a useful and psychometrically sound instrument to assess fatigue in Portuguese workers.

The strength of this structure certified the importance of the five dimensions in defining the construct fatigue.

The results of confirmatory factorial analysis of the theoretical five-factor model (nested model) did not provide satisfactory fit indexes. According to this model, *Lack of energy* was defined as a general latent factor, which represents much of the common variance in all items. Interestingly, the results of the current study support a five factor model, with 20 variables distributed on five latent factors, in contrast to previous studies (Åhsberg 2000; González Gutiérrez et al. 2005). Accordingly, Byström, Hanse, & Kjellberg (2004) found that the relationship between appraised psychological workload and musculoskeletal symptoms are not mediated by *Lack of energy*, suggesting that this factor is not sufficient to describe the role of fatigue in the development of musculoskeletal symptoms.

All items had high loadings that suggest a stronger factor contribution to those variables. Data regarding factorial weights and the good fit of the model confirm factorial validity of the instrument and justify the decision not to remove items of the scale. Additionally, it was found that all dimensions of the instrument had convergent and discriminant validity.

The Portuguese version of the SOFI demonstrated a good internal consistency. The reliability coefficient (Cronbach's alpha) were quite similar to those obtained in the Chinese version (with 25 items) (Leung et al., 2004) and higher than in the Spanish version (with 15 items) (González Gutiérrez et al., 2005). High Cronbach's alpha coefficients for the five sub-scales and SOFI total scale, indicate that the items of the Portuguese version of SOFI are highly homogeneous for the sample under study. The results regarding CR suggest the same pattern.

The rigorous process of translation and cultural adaptation, and the study of several psychometric properties, were the main strengths of this research. However, a main limitation of the present study is related to sample size and sampling technique. Indeed, as subjects were recruited by convenience, generalizability of the results to other samples of workers is limited. Furthermore, the fact that the sample is mainly constituted of women may have cause some bias.

4.5. Conclusion

In conclusion, results suggest that the Portuguese version of SOFI is a psychometrically robust self-report measure of perceived fatigue in a sample of assembly workers. Consequently, SOFI seems to be a valuable and user-friendly tool for ergonomists, occupational health practitioners and researchers to assess fatigue in industrial settings, allowing a greater involvement of workers in organizational decisions, namely related to individual job design, in order to improve workers' quality of life and health.

However, as the study of the reliability and validity of an instrument is a continuous process of analysis, further research is needed considering that the psychometric evidence presented in this study does not guarantee total invariance inter-contexts. Future longitudinal research is needed to examine the test–retest reliability of the Portuguese SOFI and more studies about its validity should be developed, in particular, studies regarding the invariance in different occupational groups.

4.6. References

Åhsberg, E. (2000). Dimensions of fatigue in different working populations. *Scandinavian Journal of Psychology*, *41*(3), 231–241.

Åhsberg, E., & Fürst, C. J. (2001). Dimensions of fatigue during radiotherapy--an application of the Swedish Occupational Fatigue Inventory (SOFI) on cancer patients. *Acta Oncologica*, *40*(1), 37–43.

Åhsberg, E., & Gamberale, F. (1998). Perceived fatigue during physical work: An experimental evaluation of a fatigue inventory. *International Journal of Industrial Ergonomics*, *21*(2), 117–131.

Åhsberg, E., Gamberale, F., & Gustafsson, K. (2000). Perceived fatigue after mental work: an experimental evaluation of a fatigue inventory. *Ergonomics*, *43*(2), 252–268.

Åhsberg, E., Gamberale, F., & Kjellberg, A. (1997). Perceived quality of fatigue during different occupational tasks development of a questionnaire. *International Journal of Industrial Ergonomics*, *20*(2), 121–135.

Åhsberg, E., Kecklund, G., Åkerstedt, T., & Francesco Gamberale. (2000). Shiftwork and different dimensions of fatigue. *International Journal of Industrial Ergonomics*, *26*(4), 457–465.

Bültmann, U., Kant, I., van Amelsvoort, L. G., van den Brandt, P. A., & Kasl, S. V. (2001). Differences in fatigue and psychological distress across occupations: results from the Maastricht Cohort Study of Fatigue at Work. *Journal of Occupational and Environmental Medicine, 43*(11), 976–983.

Byström, P., Hanse, J. A. N. J., & Kjellberg, A. (2004). Appraised psychological workload, musculoskeletal symptoms, and the mediating effect of fatigue: A structural equation modeling approach. *Scandinavian Journal of Psychology*, *45*(4), 331–341.

Coelho, T., Santos, R., Paul, C., Gobbens, R. J., & Fernandes, L. (2014). Portuguese version of the Tilburg Frailty Indicator: Transcultural adaptation and psychometric validation. *Geriatrics & Gerontology International*. doi:10.1111/ggi.12373

Dawson, D., Ian Noy, Y., Härmä, M., Kerstedt, T., & Belenky, G. (2011). Modelling fatigue and the use of fatigue models in work settings. *Accident Analysis and Prevention*, *43*(2), 549-564.

Dinges, D. F. (1995). An overview of sleepiness and accidents. *Journal of Sleep Research*, *4*(S2), 4–14.

Fornell, C., & Larcker, D. F. (1981). Evaluating structural equation models with unobservable variables and measurements error. *Journal of Marketing Research*, *18*(1), 39–50.

Gander, P., Hartley, L., Powell, D., Cabon, P., Hitchcock, E., Mills, A., & Popkin, S. (2011). Fatigue risk management: Organizational factors at the regulatory and industry/company level. *Accident Analysis and Prevention*, *43*(2), 573–590.

Gershon, P., Shinar, D., & Ronen, A. (2009). Evaluation of experience-based fatigue countermeasures. *Accident Analysis and Prevention*, *41*(5), 969–975.

González Gutiérrez, J. L., Jiménez, B. M., Hernández, E. G., & López, A. L. (2005). Spanish version of the Swedish Occupational Fatigue Inventory (SOFI): Factorial replication, reliability and validity. *International Journal of Industrial Ergonomics*, *35*(8), 737–746.

Hagelin, C. L., Wengström, Y., Ahsberg, E., & Fürst, C. J. (2009). Fatigue dimensions in patients with advanced cancer in relation to time of survival and quality of life. *Palliative Medicine*, *23*(2), 171–178.

Janssen, N., & Nijhuis, F. J. N. (2004). Associations between positive changes in perceived work characteristics and changes in fatigue. *Journal of Occupational and Environmental Medicine*, *46*(8), 866–875.

Johansson, S., Ytterberg, C., Back, B., Holmqvist, L. W., & von Koch, L. (2008). The Swedish Occupational Fatigue Inventory in people with multiple sclerosis. *Journal of Rehabilitation Medicine*, *40*(9), 737–743.

Jorgensen, R. (2008). Chronic fatigue: An evolutionary concept analysis. *Journal of Advanced Nursing*, *63*(2), 199–207.

Karlson, B., Eek, F. C., Hansen, Å. M., Garde, A. H., Österberg, K., & Øbæk, P. (2006). Diurnal cortisol pattern of shift workers on a workday and a day off. *Scandinavian Journal of Work, Environment and Health, Suppl. 2,* 27–34.

Kenny, G. P., Yardley, J. E., Martineau, L., & Jay, O. (2008). Physical work capacity in older adults: Implications for the aging worker. *American Journal of Industrial Medicine*, *51*(8), 610-25.

Krupinski, E. A., & Berbaum, K. S. (2010). Does reader visual fatigue impact interpretation accuracy? *Proc. SPIE*, *7627*, 76270M–76270M–6.

Leung, A. W. S., Chan, C. C. H., & He, J. (2004). Structural stability and reliability of the Swedish occupational fatigue inventory among Chinese VDT workers. *Applied Ergonomics*, *35*(3), 233–241.

Leung, A. W. S., Chan, C. C. H., Ng, J. J. M., & Wong, P. C. C. (2006). Factors contributing to officers' fatigue in high-speed maritime craft operations. *Applied Ergonomics*, *37*(5), 565–576.

Marôco, J. (2010). *Análise de Equações Estruturais: Fundamentos teóricos, Software & Aplicações*. Pêro Pinheiro: ReportNumber, Lda.

Mathiassen, S. E., Hallman, D. M., Lyskov, E., & Hygge, S. (2014). Can Cognitive Activities during Breaks in Repetitive Manual Work Accelerate Recovery from Fatigue? A Controlled Experiment. *PLoS ONE*, *9*(11), e112090.

Mizuno, K., Tajima, K., Watanabe, Y., & Kuratsune, H. (2014). Fatigue correlates with the decrease in parasympathetic sinus modulation induced by a cognitive challenge. *Behavioral and Brain Functions*, *10*, 25.

Muller, R., Carter, A., & Williamson, A. (2008). Epidemiological diagnosis of occupational fatigue in a fly-in-fly-out operation of the mineral industry. *Annals of Occupational Hygiene*, *52*(1), 63–72.

Persson, R., Garde, A. H., Hansen, Å. ̊ M., Ørbæk, P., & Ohlsson, K. (2003). The influence of production systems on self-reported arousal, sleepiness, physical exertion and fatigue - Consequences of increasing mechanization. *Stress and Health*, *19*(3), 163–171.

Phillips, R. O. (2015). A review of definitions of fatigue – And a step towards a whole definition. *Transportation Research Part F: Traffic Psychology and Behaviour*, *29*, 48–56.

Ream, E., & Richardson, A. (1996). Fatigue: A concept analysis. *International Journal of Nursing Studies*, *33*(5), 519–529.

Saito, K. (1999). Measurement of fatigue in industries. *Industrial Health*, *37*(2), 134–142.

Tanaka, M., Yamada, H., Nakamura, T., & Watanabe, Y. (2012). Effects of pellet stove on recovery from mental fatigue. *Medical Science Monitor: International Medical Journal of Experimental and Clinical Research*, *18*(3), CR148–CR153.

Terwee, C. B., Bot, S. D. M., de Boer, M. R., van der Windt, D. A. W. M., Knol, D. L., Dekker, J., … de Vet, H. C. W. (2007). Quality criteria were proposed for measurement properties of health status questionnaires. *Journal of Clinical Epidemiology*, *60*(1), 34–42.

Wild, D., Grove, A., Martin, M., Eremenco, S., McElroy, S., Verjee-Lorenz, A., & Erikson, P. (2005). Principles of good practice for the translation and cultural adaptation process for patient-reported outcomes (PRO) measures: Report of the ISPOR Task Force for Translation and Cultural Adaptation. *Value in Health*, *8*(2), 94–104.

Williamson, A., Friswell, R., & Feyer, A. (2004). *Fatigue and performance in heavy truck drivers working day shift, night shift or ratating shifts*. Melbourn, Victoria. Retrieved from http://ntc.wdu.com.au/filemedia/Reports/FatiPerfHVDayNightDec2004.pdf

Williamson, A., Lombardi, D. A., Folkard, S., Stutts, J., Courtney, T. K., & Connor, J. L. (2011). The link between fatigue and safety. *Accident Analysis and Prevention*, *43*(2), 498–515.

CHAPTER 5: Development of fatigue in wrist muscles during assembly work in a real-life occupational setting

Abstract

Analysis of muscle fatigue during a workday can be used to improve the management of time aspects of work. The purpose of this study was to estimate muscle fatigue of wrist muscles and to determine subjective fatigue experienced by participants over the course of a workday. Thirty-four female assembly workers participated in this study. Objective and subjective manifestations of fatigue were obtained via electromyography (EMG) during test contractions (15% MVC) and ratings of perceived fatigue, respectively. Linear regression analysis of root mean square (RMS) and median frequency (MF) of the EMG signal demonstrated that the muscles started a fatigue process. However, no significant differences were found throughout the workday. On the other hand, perceived fatigue increased significantly. Taken together, these results suggest a change in the pattern of motor unit recruitment of the muscles under study, yet there was no consistent evidence of fatigue induced by working time.

Practitioner Summary: Work in assembly lines requires a good management of time aspects. Electromyographical manifestations of fatigue as well as perceived fatigue were determined during 8h of assembly work. The results of the EMG parameters indicated that wrist muscles had risk of fatigue; however, they were not significantly affected by working hours.

Keywords: Assembly work, muscle fatigue, electromyography, wrist muscles.

5.1. Introduction

Work-related upper limb musculoskeletal disorders (WRULDs) are prevalent across Europe and have a great effect on the quality of life of workers and contribute to absenteeism (Buckle & Jason Devereux, 2002; Punnett & Wegman, 2004; Stewart, Ricci, Chee, & Morganstein, 2003). The risk factors for the development of WRULDs can be grouped into work physical requirements and into individual, organizational and psychosocial factors (Devereux, Vlachonikolis, & Buckle, 2002; Hoe, Urquhart, Kelsall, & Sim, 2012; Leclerc et al., 1998). Revolutionary changes in work organization over the years result in several effects on musculoskeletal health. Mass production, automation of workstations and implementation of manufacture production systems, such as Lean Production System (LPS), and disregarding human factors can result in the development of musculoskeletal disorders (Wells, Mathiassen, Medbo, & Winkel, 2007). According to Mathiassen (2006), the automation of work processes result in more monotonous and repetitive work. Several authors have reported that repetitive manual work is a risk factor associated with wrist and hand disorders, such as tendon-related disorders, carpal tunnel syndrome (CTS) and cramping of the hand and forearm (Hansson et al., 2000; Latko et al., 1999; Muggleton, Allen, & Chappell, 1999; Viikari-Juntura & Silverstein, 1999). Thomsen et al. (2007) reported that an increase in the duration of repetitive work could result in an increased risk of hand-wrist pain. Assembly work is an example of work where the procedures are strictly standardized with short cycle times (less than 30 s), little task variation, repetitive wrist motions and reduced breaks or pauses. In these tasks, an adequate management of the time aspects of work, such as work duration, is crucial to decrease the risk of musculoskeletal disorders and muscle fatigue development. Muscle fatigue can be used as a biomarker for predicting the development of disorders (Marras, William, & Karwowski 2006). The assessment of this biomarker may be helpful to prevent the development of work-related musculoskeletal disorders (WRMSDs) (Madeleine, 2010) and to design ergonomic work stations, to plan appropriate work-rest patterns and to assess the progression of disorders. Electromyography (EMG) is the most common objective method used to assess muscle fatigue. EMG parameters commonly used to describe muscle fatigue are root mean square (RMS), mean power frequency (MPF), or median frequency (MF). Several studies have reported that fatigue occurs when time domain parameters, such as the mean amplitude and RMS amplitude increase (Larivière, Arsenault, Gravel, Gagnon, & Loisel, 2003), and MPF or MF decrease (De Luca, Sabbahi, & Roy 1986; Ament et al. 1996; Balasubramanian, Adalarasu, and Regulapati 2009). During isometric contraction, the MF of the power spectrum will be determined largely by the number and type of motor units activated (Elfving, Dedering, & Németh, 2003). According to some authors, the MF is used as an index of power spectral alterations (Hägg 1992; Hägg & Kadefors 1996; De Luca 1997) and is less sensitive to noise and more sensitive to the biochemical and physiological processes that occur within the muscles during sustained contractions (De Luca 1984; Merletti, Knaflitz, & De Luca 1992). The EMG parameters in ergonomics can be used to analyze the development of muscle fatigue over time or during entire working day, namely in field studies. Regression analysis of RMS and MPF or MF values during contraction periods of known force in the standardized posture are used in the analysis as characteristics of temporal behavior of the EMG (Merletti, Lo Conte, & Orizio 1991; Hägg, Luttmann, & Jäger 2000).

Perceived fatigue or discomfort has been measured using uni-dimensional scales, such as Rating of Perceived Exertion (RPE) (Borg 1990; Borg 1998), and Category Ratio 10 (CR10) (Borg 1982; Borg 1998) or multidimensional scale, such as Swedish Occupational Fatigue Inventory (SOFI) (Åhsberg, Gamberale, & Kjellberg, 1997). Some studies have reported an increase in the subjective ratings accompanied with an increase in amplitude and a decrease in the frequency of muscle under study during low-force work (Bosch, de Looze, & van Dieën, 2007; Kimura, Sato, Ochi, Hosoya, & Sadoyama, 2007; Sundelin & Hagberg, 1992). However, Nakata, Hagner, & Jonsson (1992) found no objective sign of fatigue and the perceived exertion and discomfort increase. Thus, more research is needed to understand the relationship between objective and subjective fatigue indicators, namely during real work task situations.

The development of muscle fatigue during low-force repetitive work, such as assembly tasks, has been investigated by some researchers (Mathiassen & Winkel 1996; Bosch et al. 2011; Palmerud et al. 2012). Bosch et al. (2012) investigated temporal changes in movement strategy and performance during 1-h repetitive arm reaching task. EMG amplitude and MPF results showed an increase in muscle fatigue of the upper trapezius muscle during a prolonged repetitive task. Similar results were found by Bennie et al. (2002) and Dennerlein et al. (2003) in a controlled laboratory experiment, when investigating the electromyographic activity of the human extensor carpi ulnaris muscle during 8-h of repetitive ulnar deviation task. Considering the need to develop more research in real working conditions, the aim of this study was to investigate muscle fatigue over a working day in a real-life occupational setting using the EMG signal of the extensor carpi radialis and flexor carpi radialis muscle during assembly work. In addition, this study also aimed to determine the relationship between EMG indicators of fatigue and workers' perceived fatigue.

5.2. Materials and Methods

This study was performed in a company that produces different types of mechanical cables for the automotive industry. This company has implemented the LPS, and assembly lines constitute most of the production area. All equipment has andon and poka-yoke systems to detect abnormalities of the products and to notify the operators. The company has three fixed shifts (morning: 6:00 a.m.-14:00 p.m. (A); afternoon: 14:00 p.m.-22:00 p.m. (B); night: 22:00 p.m.-6:00 a.m. (C)). Each shift has one break of 15 min.

5.2.1. Subjects

Thirty-four female assemblers were selected to participate in this study. The participants had work experience between 12 and 144 months and were right-handed. They completed a health questionnaire and signed an informed consent approved by the School of Allied Health Technologies, Polytechnic Institute of Porto Ethics Committee. None of the subjects reported any pain or musculoskeletal disorders. They have a continuous work schedule of 8 h with 15 min of break. Table 9 shows the demographics, characteristics, and anthropometric dimensions of the sample.

Table 9. Demographic characteristics and anthropometric dimensions (n=31).

	Range	**Mean**	**SD**
Age (years)	19-45	31.5	7.0
Anthropometric dimensions (standing) (cm)			
Stature	146.0-170.0	158.8	5.6
Eye height	134.15-157.5	147.6	5.1
Shoulder height	118.7-140.6	131.9	5.6
Elbow height	83.1-105.1	100.4	5.7
Wrist height	60.1-80.1	70.7	4.1
Shoulder Breadth (Bideltoid)	37.6-47.0	41.1	2.3
Elbow-Wrist Distance	27.4-35.2	30.6	1.9
Forward Reach	58.8-72.2	65.4	3.4
Wrist Circumference	13.5-18.5	15.1	1.0
Forearm Circumference	20.3-26.7	22.7	1.7
Weight (Kg)	44.9-81.2	58.8	9.3
BMI (Kg/m2)	18.0-33.3	23.2	3.7

5.2.2. Tasks

The workers adopted standing static postures using the upper limbs to place the materials in the equipment and to press the control buttons. The tasks developed by participants selected were: a) assemble and press terminals of the conduit; b) assemble cable in the conduit and cut the edge of the cable; c) press second cable terminal; d) rehearsal and recording ink into the final product. The cycle time in each task was approximately 5.5 seconds. According to the literature, the intensity levels of this type of work activity were below 20% MVC (Westgaard, Jansen, and Jensen 1996), with highly repetitive movements of the wrist.

5.2.3. Procedures and instrumentation

Before starting work, workers were instructed to perform a maximal handgrip force with their right hand using an electronic handgrip dynamometer (model TSD121C, BioPac Systems, Goleta, CA). The grip selected for trials was the pinch grip due to its predominance during assembly tasks. Three trials with 4 seconds of duration, intervaled with 1-min of rest, were used to estimate the maximal level of force (Brown & Weir, 2001). The participants sat upright with their feet on the floor, and their knees at 90º. In addition, their shoulders were parallel to the floor and their forearm was flexed (105º) horizontally and supported, with the forearm and wrist in a neutral position. The maximal level of force was determined by choosing the greatest of three attempts at generating the maximal voluntary effort. Handgrip force was registered using the MP36R Workstation model from *Biopac Systems* Inc., Santa Barbara, CA USA. This system allowed the visualization of the exerted force in the computer screen, so that verbal motivation and visual feedback of the data acquisition system were used to encourage participants to perform maximal efforts.

Surface EMG signals were recorded from extensor carpi radialis muscle (ECR) and flexor carpi radialis muscle (FCR) during maximum voluntary contraction (MVC) trials using the same system. These muscles cooperate to perform prehensile activities and to stabilize the wrist. Prior to data collection, the forearm skin surfaces were prepared with an abrasive gel (Nuprep Skin Prep Gel) and cleansed with alcohol to reduce the electrical resistance to less than 5000 Ω. Skin impedance was measured using the Noraxonr® Impedance Checker system (Noraxon, Scottsdale, Arizona). Disposable pediatric Ag/AgCl electrodes with a skin contact, and inter-electrode distance of 20 mm, were placed parallel to the muscle fibers according to the SENIAM (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). The electrodes were placed in the following manner: a) FCR – one third of the distance from the proximal end of a line from the medial epicondyle to the distal head of the radius; ECR – two fingerbreadths distal to the lateral epicondyle (Mogk & Keir, 2003b). Ground electrodes were placed over both olecraneums (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). Before applying the electrodes, the muscle belly location was confirmed by palpation during muscle-specific movements of the wrist.

To measure changes in muscle activity, after the three MVCs and an additional rest period of 2 minutes, in the posture described above, participants performed an isometric test contraction with a duration of 180 s at a predetermined force level corresponding to 15% of MVC. Subjects maintained the set force level by viewing it on the computer screen. Recordings were obtained three times during the workday (before starting, before break and at the end of the day). Electrodes were kept in the same positions throughout the workday. EMG activity was collected continuously during these test contractions. Importantly, the measurements did not interfere with the normal working time. A scheme of the protocol used in this study is presented in Figure 9. As shown in Figure 9, data collection in the afternoon shift (B1, B2) varied according to the break time.

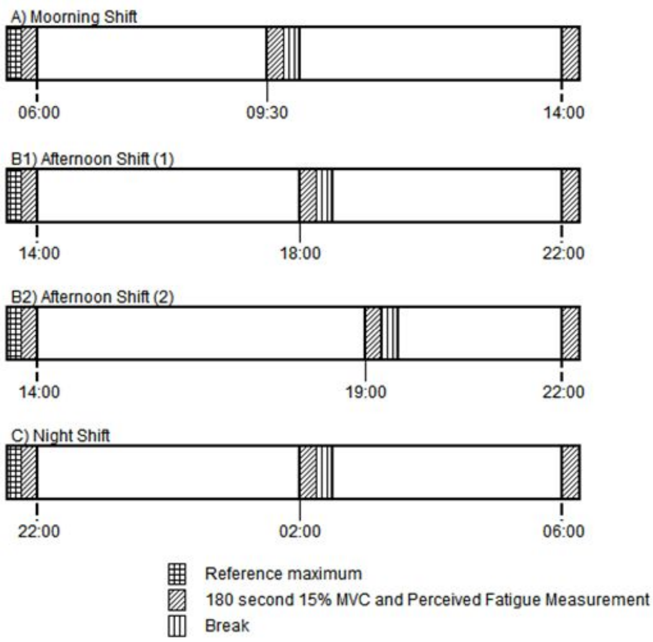


Figure 9. Protocol scheme.

5.2.4. EMG data acquisition and processing

The EMG and force signals were acquired at a sample rate of 1000 Hz for subsequent analysis with the Acqknowledge 4.1 software for Mac OS X (Biopac Systems, Inc. USA). The input impedance and common mode rejection ratio (CMRR) of the MP36R system were 2MΩ and 110 dB, respectively. Signals were band-pass filtered at 20–500 Hz and RMS processed for consecutive segments of 100 ms.

EMG-based measures of muscle fatigue (RMS and MF) were obtained from a 1 s window in each reference contraction (at 15%MVC). The RMS amplitude values were normalized to the EMG values measured during the MVC at the start of the working day. The MF was determined using a Fast Fourier transform (FFT) of the EMG signal at each 1-second interval with a 50% overlapping Hamming window. MF changes during contraction period were also analyzed by linear regression (Merletti et al., 1991). The slope of the MF regression line was normalized by ($NMF_{slope} = \frac{MFslope}{MFinit} \times 100\%$), according to Coorevits et al. (2008), due to the potential differences subcutaneous layers between subjects and between different muscles of the subject. The initial median frequency (MF_{init}) was defined as the intercept of the regression line, and the median frequency slope (MF_{slope}) was determined as the slope of the regression line. The negative slope of the regression line of MF is commonly used as an indicator of the muscle's fatigability (Hägg, Luttmann, & Jäger 2000; Larivièreet al. 2003). Additionally, the MF values of each test contraction at 15% were determined and normalized to the measurement at the beginning of the working day. Linear regression analysis was also performed on RMS as a function of time. The positive slope of the regression line of RMS is interpreted as an indicator of fatigue (Hägg, Luttmann, & Jäger 2000; Larivièreet al. 2003).

Due to the poor quality of the EMG signal in the contraction test trial, the muscle activity of three participants could not be determined (n = 31).

5.2.5. Perceived fatigue

After each EMG sampling period, the subject was asked to rate the perceived exertion using the CR-10 Borg scale (Borg, 1998). In addition, subjective fatigue was rated using the Swedish Occupational Fatigue Inventory (SOFI) (Åhsberg et al., 1997). SOFI is an instrument for the multidimensional evaluation of work-related fatigue. This questionnaire measures fatigue in five dimensions: lack of energy, physical exertion, physical discomfort, lack of motivation and sleepiness. For every expression, the participants rated how they felt at the moment, using a numerical scale ranging from 0 (not at all) and 6 (to a very high degree).

5.2.6. Statistical analysis

All statistical analyses were performed using IBM SPSS™ Statistics 20. The differences in muscle activity (EMG parameters) during the three moments of the workday were compared with repeated-measure ANOVA. *P*-Values were based on the degrees of freedom corrected with Greenhouse-Geisser's epsilon. In addition, t-tests for paired samples were used to confirm if there were any differences between the wrist muscles studied. Pearson correlation coefficients were also calculated to determine the relationships between objective EMG variables and subjective fatigue. Significance was established at $p<0.05$.

5.3. Results

5.3.1. EMG measurements

The normalized regression coefficient of the median frequencies (NMF_{slope}) values and RMS slope values are presented in Figures 10 and 11, respectively. No significant differences in NMF_{slope} values were found (FCR: p=0.445; ECR: p=0.088) for the EMG measurements performed during the workday. Although FCR presented a higher rate of decline of NMF_{slope}, no significant differences were found between muscles for the three measured moments (p=0.583; p=0.704; p=0.395). For both muscles, it is evident that the NMF_{slope} values are higher (less negative) at the end of the day, indicating less fatigue. However, RMS slope values for FCR and ECR had a progressive increase throughout the day, except in the last assessment of ECR, which showed a decrease. Statistically, no significant temporal changes for this parameter were found (FRC: p=0.344; ECR: p=0.904). Concerning the MF values of each test contraction, significant temporal changes were only found for ECR (p=0.000).

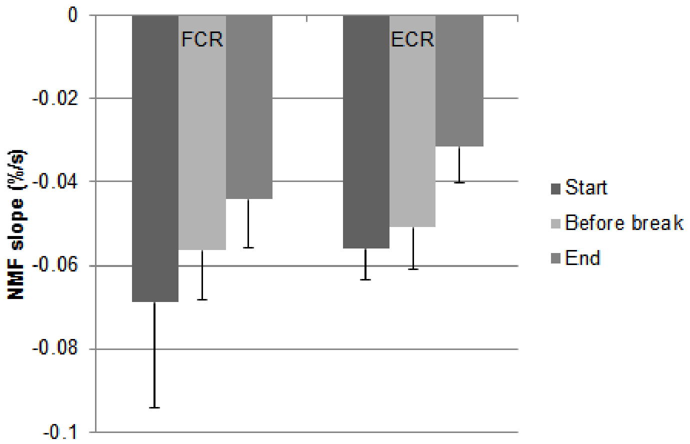


Figure 10. NMF_{slope} values (%/s) of the flexor carpi radialis muscle (FCR) and extensor carpi radialis muscle (ECR). Bars represent the standard error of the mean (SEM) (n=31).

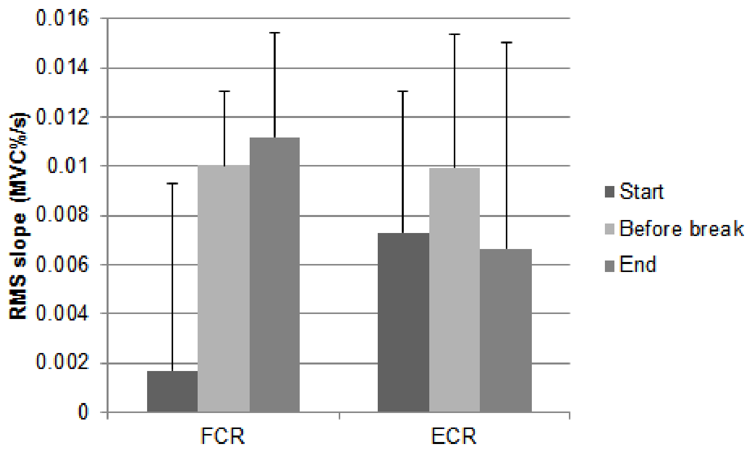


Figure 11. RMS slope values (MVC%/s) of the flexor carpi radialis muscle (FCR) and extensor carpi radialis muscle (ECR). Bars represent the standard error of the mean (SEM) (n=31).

5.3.2. Perceived fatigue

Figure 12 shows the variation of SOFI and Borg CR-10 scores during the workday. Perceived fatigue increased significantly across time (SOFI: $p<0.05$; CR-10 Borg scale: $p<0.05$).

The CR-10 Borg scale was rated between 0.95 at the start and 1.30 at the end of the day. All dimensions of SOFI rating increased with time and significant differences were found for lack of energy ($p<0.05$), physical exertion ($p<0.05$), physical discomfort ($p=0.045$), lack of motivation ($p<0.05$) and sleepiness ($p<0.029$).

A post-hoc test showed a significant increase in the scores in the two rating scales throughout the workday ($p<0.05$). CR-10 Borg ratings showed a moderate correlation with lack of energy (r=0.527; p=0.002), physical exertion (r=0.527; p=0.002), physical discomfort (r=0.361; p=0.046) and sleepiness (r=0.452; p=0.011). No relationship was found between the subject characteristics and ratings (CR-10 Borg scale: age: r=0.129 p=0.489; body mass index: r=0.052 p=0.781; SOFI: age: r=-0.028 p=0.880; body mass index: r=0.043 p=0.819). In general, no significant correlation was found between the EMG parameters and subjective ratings.

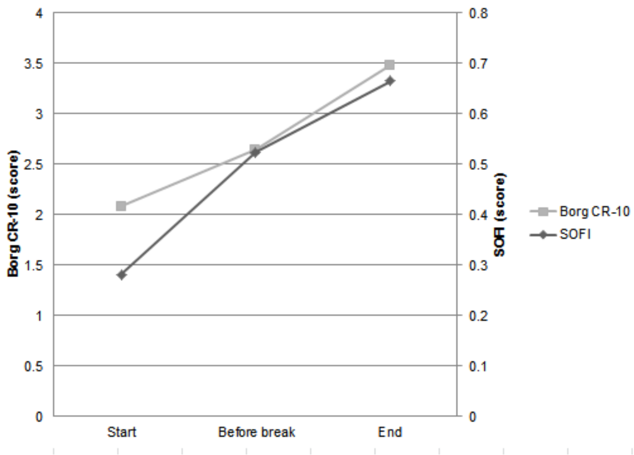


Figure 12. Temporal changes in perceived fatigue (n=31).

5.4. Discussion

In this study, we investigated the development of EMG manifestations of muscle fatigue of FCR and ECR during a normal day (8 h) of assembly work. Expectedly, the slopes of the NMF/time relationships were negative for both muscles, which is an indicator that the muscles started a fatigue process (Hägg, Luttmann, & Jäger 2000; Gaudreault et al. 2005). However, NMF_{slopes} values increased (not significantly) over the course of the workday (see Figure 10). In addition, the RMS slope values increased (except in the end of the day for ECR muscle) (see Figure 11). Overall, there appears to be a change in the recruitment pattern of motor units during the workday as demonstrated by the increase in normalized RMS slope, which is an indicator of fatigue. Thus, these results demonstrated that there is no consistent evidence of EMG manifestations of muscle fatigue over the course of the workday, indicating that the fatigue response may be affected by other factors. The increase in the EMG amplitude may suggest additional recruitment motor units with higher conduction velocities that can counteract downward shifting of the MF (Hägg 1992; Hägg & Kadefors 1996; Kupa et al. 1995; de Looze, Bosch, & van Dieën 2009). Christensen et al. (2000) also reported no significant differences in the increase in RMS amplitude and in the decrease in the MPF of the EMG signal at the beginning and at the end of the work period, between two groups of meat cutters. In another study, Nakata, Hagner, & Jonsson (1992) revealed that there was no fatigue development in the trapezius muscle during simulated assembly work and hypothesized that the increased amplitude might have resulted from a change in muscle temperature. However, Bosch, de Looze, & van Dieën (2007) reported that an increase in the amplitude of the EMG signal was accompanied by a decrease in the MPF over the course of a working day for the trapezius muscle. The NMF slope values can also be explained by the changes in work posture or technique over time due to fatigue, which distribute the load within the muscle measured or between different muscles (Balasubramanian, Dutt, & Rai, 2011; de Looze et al., 2009). The FCR muscle had the greatest decline in MF compared to the ECR muscle (not significant), which can be explained by a higher recruitment of FCR muscle during assembly tasks. Results of EMG parameters may also have been affected by crosstalk phenomenon due the close proximity of forearm muscles and their small surface area (Mogk & Keir 2003b).

This field study also exhibited confounding variables that may have affected the results, such as the introduction of additional micro-breaks during work. The experimental technique of this study allowed control of the force produced by muscles under examination, which would not be possible if the evaluations were performed in the workstation. The acquisition of kinematic data during the test contraction improved posture control; however, under field conditions, it is difficult to install systems for motion capture. In addition, field research has some limitations compared with controlled laboratory studies. Confounding factors, such as disturbances in production (production breaks caused by breakdown of equipment or lack of raw materials) and lack of control of the task duration may have a significant effect on the results.

Despite the limitations of the using mechanomyogram (MMG) in field studies, this method has been recommended as a complementary method to detect muscle fatigue induced by low force contraction (Madeleine, Bajaj, Søgaard, & Arendt-Nielsen, 2001; Søgaard, Blangsted, Jørgensen, Madeleine, & Sjøgaard, 2003).

Subjective fatigue gradually increased over time as shown by the perceived fatigue ratings. Mathiassen & Winkel (1996) also reported an increase in fatigue in the shoulder-neck region during a day of assembly work. However, in this study, no consistent results were found with regard to the relationship between perceived fatigue and EMG manifestations of fatigue (see Table 9). Our findings are similar with the results of Bosch, de Looze, & van Dieën (2007), who studied repetitive low-intensity assembly work with normal 8-h working days and extended 9.5-h working days.

5.5. Conclusions

The present study did not demonstrate that working time had a significant effect on the EMG manifestations of muscle fatigue in the muscles under study. However, the RMS slope values obtained over the workday suggest that further research is needed to understand the mechanisms in terms of muscle recruitment patterns during low-load repetitive work. Cumulative exposure to repetitive work causes significant physiological changes in muscles; therefore, it would be interesting to investigate the same muscles for a normal work week. In addition, complementary assessment can be used to investigate the effect of this type of work on proprioception of the wrist joint.

5.6. References

Åhsberg, E., Gamberale, F., & Kjellberg, A. (1997). Perceived quality of fatigue during different occupational tasks development of a questionnaire. *International Journal of Industrial Ergonomics*, *20*(2), 121–135.

Ament, W., Bonga, G. J., Hof, A. L., & Verkerke, G. J. (1996). *Electromyogram median power frequency in dynamic exercise at medium exercise intensities. European Journal of Applied Physiology and Occupational Physiology*, *74*(1-2), 180-186.

Balasubramanian, V., Adalarasu, K., & Regulapati, R. (2009). Comparing dynamic and stationary standing postures in an assembly task. *International Journal of Industrial Ergonomics*, *39*(5), 649–654.

Balasubramanian, V., Dutt, A., & Rai, S. (2011). Analysis of muscle fatigue in helicopter pilots. *Applied Ergonomics*, *42*(6), 913–918.

Bennie, K. J., Ciriello, V. M., Johnson, P. W., & Dennerlein, J. T. (2002). Electromyographic activity of the human extensor carpi ulnaris muscle changes with exposure to repetitive ulnar deviation. *European Journal of Applied Physiology*, *88*(1-2), 5–12.

Borg, G. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise*, *14*(5), 377–381.

Borg, G. (1990). Psychophysical scaling with applications in physical work and the perception of exertion. *Scandinavian Journal of Work, Environment and Health*, *16*(Suppl. 1), 55–58.

Borg, G. (1998). *Borg's Perceived Exertion and Pain Scales*. Human Kinetics.

Bosch, T., de Looze, M. P., & van Dieën, J. H. (2007). Development of fatigue and discomfort in the upper trapezius muscle during light manual work. *Ergonomics*, *50*(2), 161–177.

Bosch, T., Mathiassen, S. E., Hallman, D., de Looze, M. P., Lyskov, E., Visser, B., & van Dieën, J. H. (2012). Temporal strategy and performance during a fatiguing short-cycle repetitive task. *Ergonomics*, *55*(8), 863-873.

Bosch, T., Mathiassen, S. E., Visser, B., de Looze, M. P., & van Dieën, J. H. (2011). The effect of work pace on workload, motor variability and fatigue during simulated light assembly work. *Ergonomics*, *54*(2), 154–168.

Brown, L. E., & Weir, J. P. (2001). ASEP procedures recommendation I: accurate assessment of muscular strength and power. *Journal of Exercise Physiology*, *4*(3), 1–21.

Buckle, P. W., & Jason Devereux, J. (2002). The nature of work-related neck and upper limb musculoskeletal disorders. *Applied Ergonomics*, *33*(3), 207–217.

Christensen, H., Sogaard, K., Pilegaard, M., & Olsen Engineer, H. B. (2000). The importance of the work/rest pattern as a risk factor in repetitive monotonous work. *International Journal of Industrial Ergonomics*, *25*(4), 367–373.

Coorevits, P., Danneels, L., Cambier, D., Ramon, H., & Vanderstraeten, G. (2008). Assessment of the validity of the Biering-Sørensen test for measuring back muscle fatigue based on EMG median frequency characteristics of back and hip muscles. *Journal of Electromyography and Kinesiology*, *18*(6), 997–1005.

De Looze, M., Bosch, T., & van Dieën, J. (2009). Manifestations of shoulder fatigue in prolonged activities involving low-force contractions. *Ergonomics*, *52*(4), 428–437.

De Luca, C. J. (1984). Myoelectrical manifestations of localized muscular fatigue in humans. *Critical Reviews in Biomedical Engineering*, *11*(4), 251–279.

De Luca, C. J., Sabbahi, M. A., & Roy, S. H. (1986). Median frequency of the myoelectric signal. Effects of hand dominance. *European Journal of Applied Physiology and Occupational Physiology*, *55*(5), 457–464.

De Luca, C. J. (1997). The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics*, *13*(2), 135–163.

Dennerlein, J. T., Ciriello, V. M., Kerin, K. J., & Johnson, P. W. (2003). Fatigue in the forearm resulting from low-level repetitive ulnar deviation. *AIHA Journal*, *64*(6), 799–805.

Devereux, J., Vlachonikolis, I., & Buckle, P. (2002). Epidemiological study to investigate potential interaction between physical and psychosocial factors at work that may increase the risk of symptoms of musculoskeletal disorder of the neck and upper limb. *Occupational and Environmental Medicine*, *59*(4), 269–277.

Elfving, B., Dedering, Å., & Németh, G. (2003). Lumbar muscle fatigue and recovery in patients with long-term low-back trouble - Electromyography and health-related factors. *Clinical Biomechanics*, *18*(7), 619–630.

Gaudreault, N., Arsenault, A. B., Larivière, C., DeSerres, S. J., & Rivard, C. H. (2005). Assessment of the paraspinal muscles of subjects presenting an idiopathic scoliosis: an EMG pilot study. *BMC Musculoskeletal Disorders*, *6*, 14.

Hägg, G. M. (1992). Interpretation of EMG spectral alterations and alteration indexes at sustained contraction. *Journal of Applied Physiology*, *73*(4), 1211–1217.

Hägg, G. M., Kadefors, R. (1996). EMG alterations at sustained contractions with special emphasis on applications in ergonomics. In S. Kumar and A. Mital. (Ed.), *Electromyography in Ergonomics* (pp. 163–181). London: Taylor and Francis.

Hägg, G. M., Luttmann, A., & Jäger, M. (2000). Methodologies for evaluating electromyographic field data in ergonomics. *Journal of Electromyography and Kinesiology*, *10*(5), 301-312.

Hansson, G. Å., Balogh, I., Ohlsson, K., Pålsson, B., Rylander, L., & Skerfving, S. (2000). Impact of physical exposure on neck and upper limb disorders in female workers. *Applied Ergonomics*, *31*(3), 301–310.

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology*, *10*(5), 361–374.

Hoe, V. C., Urquhart, D. M., Kelsall, H. L., & Sim, M. R. (2012). Ergonomic design and training for preventing work-related musculoskeletal disorders of the upper limb and neck in adults. *Cochrane Database of Systematic Reviews*, *8*, CD008570.

Kimura, M., Sato, H., Ochi, M., Hosoya, S., & Sadoyama, T. (2007). Electromyogram and perceived fatigue changes in the trapezius muscle during typewriting and recovery. *European Journal of Applied Physiology*, *100*(1), 89–96.

Kupa, E. J., Roy, S. H., Kandarian, S. C., & De Luca, C. J. (1995). Effects of muscle fiber type and size on EMG median frequency and conduction velocity. *Journal of Applied Physiology*, *79*(1), 23–32.

Larivière, C., Arsenault, A. B., Gravel, D., Gagnon, D., & Loisel, P. (2003). Surface electromyography assessment of back muscle intrinsic properties. *Journal of Electromyography and Kinesiology*, *13*(4), 305–318.

Latko, W. A., Armstrong, T. J., Franzblau, A., Ulin, S. S., Werner, R. A., & Albers, J. W. (1999). Cross-sectional study of the relationship between repetitive work and the prevalence of upper limb musculoskeletal disorders. *American Journal of Industrial Medicine*, *36*(2), 248–259.

Leclerc, A., Franchi, P., Cristofari, M., Delemotte, B., Mereau, P., Teyssier-Cotte, C., & Touranchet, A. (1998). Carpal tunnel syndrome and work organisation in repetitive work: a cross sectional study in France. Study Group on Repetitive Work. *Occupational and Environmental Medicine*, *55*(3), 180–187.

Madeleine, P. (2010). On functional motor adaptations: From the quantification of motor strategies to the prevention of musculoskeletal disorders in the neck-shoulder region. *Acta Physiologica*, *199*(Suppl. 679), 1–46.

Madeleine, P., Bajaj, P., Søgaard, K., & Arendt-Nielsen, L. (2001). Mechanomyography and electromyography force relationships during concentric, isometric and eccentric contractions. *Journal of Electromyography and Kinesiology*, *11*(2), 113–121.

Marras, W. S., & Karwowski, W. (2006). *Fundamentals and Assessment Tools for Occupational Ergonomics* (2nd ed.). Boca Raton: CRC Press.

Mathiassen, S. E. (2006). Diversity and variation in biomechanical exposure: What is it, and why would we like to know? *Applied Ergonomics*, *37*(4), 419–427.

Mathiassen, S. E., & Winkel, J. (1996). Physiological comparison of three interventions in light assembly work: Reduced work pace, increased break allowance and shortened working days. *International Archives of Occupational and Environmental Health*, *68*(2), 94–108.

Merletti, R., Knaflitz, M., & DeLuca, C. J. (1992). Electrically evoked myoelectric signals. *Critical Reviews in Biomedical Engineering*, *19*(4), 293–340.

Merletti, R., Lo Conte, L. R., & Orizio, C. (1991). Indices of muscle fatigue. *Journal of Electromyography and Kinesiology*, *1*(1), 20–33.

Mogk, J. P. M., & Keir, P. J. (2003a). Crosstalk in surface electromyography of the proximal forearm during gripping tasks. *Journal of Electromyography and Kinesiology*, *13*(1), 63–71.

Mogk, J. P. M., & Keir, P. J. (2003b). The effects of posture on forearm muscle loading during gripping. *Ergonomics*, *46*(9), 956–975.

Muggleton, J. M., Allen, R., & Chappell, P. H. (1999). Hand and arm injuries associated with repetitive manual work in industry: a review of disorders, risk factors and preventive measures. *Ergonomics*, *42*(5), 714–739.

Nakata, M., Hagner, I. M., & Jonsson, B. (1992). Perceived musculoskeletal discomfort and electromyography during repetitive light work. *Journal of Electromyography and Kinesiology*, *2*(2), 103–111.

Palmerud, G., Forsman, M., Neumann, W. P., & Winkel, J. (2012). Mechanical exposure implications of rationalization: A comparison of two flow strategies in a Swedish manufacturing plant. *Applied Ergonomics*, *43*(6), 1110–1121.

Punnett, L., & Wegman, D. H. (2004). Work-related musculoskeletal disorders: the epidemiologic evidence and the debate. *Journal of Electromyography and Kinesiology*, *14*(1), 13–23.

Søgaard, K., Blangsted, A. K., Jørgensen, L. V., Madeleine, P., & Sjøgaard, G. (2003). Evidence of long term muscle fatigue following prolonged intermittent contractions based on mechano- and electromyograms. *Journal of Electromyography and Kinesiology*, *13*(5), 441–450.

Stewart, W. F., Ricci, J. A., Chee, E., & Morganstein, D. (2003). Lost productive work time costs from health conditions in the United States: results from the American Productivity Audit. *Journal of Occupational and Environmental Medicine*, *45*(12), 1234–1246.

Sundelin, B. G., & Hagberg, M. (1992). Electromyographic signs of shoulder muscle fatigue in repetitive arm work paced by the Methods Time Measurement system. *Scandinavian Journal of Work, Environment and Health*, *18*(4), 262–268.

Thomsen, J. F., Mikkelsen, S., Andersen, J. H., Fallentin, N., Loft, I. P., Frost, P., … Overgaard, E. (2007). Risk factors for hand-wrist disorders in repetitive work. *Occupational and Environmental Medicine*, *64*(8), 527–533.

Viikari-Juntura, E., & Silverstein, B. (1999). Role of physical load factors in carpal tunnel syndrome. *Scandinavian Journal of Work, Environment and Health*, *25*(3), 163–185.

Wells, R., Mathiassen, S. E., Medbo, L., & Winkel, J. (2007). Time-A key issue for musculoskeletal health and manufacturing. *Applied Ergonomics*, *38*(6), 733–744.

Westgaard, R. H., Jansen, T., and Jensen, C. (1996). EMG of the neck and shoulder muscles: the relationship between muscle activity and muscle pain in occupational settings. In S. Kumar and A. Mital (Ed.), *Electromyography in ergonomics.* (pp. 227–258). London: Taylor and Francis.

CHAPTER 6: Effects of job rotation on wrist muscle fatigue and joint position sense among assembly-line workers

Abstract

Job rotation is a commonly tool used by companies to reduce the occurrence of work-related musculoskeletal disorders (WRMSDs). However, few studies have evaluated the effectiveness of this organizational measure in real-life occupational settings. Thus, the aim of this study was to investigate the effect of job rotation on wrist muscle fatigue and joint position sense in a mechanical cables assembly plant. Three groups of healthy volunteers, a total of sixteen subjects (4 assembly workers performed task rotation, 4 assembly workers performed tasks with no rotation and 8 volunteers were from the control group) performed two experimental sessions at the beginning and at the end of the week. Extensor carpi radialis muscle (ECR) and the flexor carpi radialis muscle manifestations of muscle fatigue (FCR) were obtained by surface electromyography at 15% of maximal voluntary contraction (MVC), while wrist position sense errors were assessed by electrogoniometry. Data analysis demonstrated that FCR muscle might have benefited from the rotation conditions as this muscle showed EMG signs of fatigue in the group without rotation during the two sessions. Overall, the three groups showed a trend to increase position error for flexion after a week of work. Implementation of a rotation system in standardized and short-cycle tasks, as assembly tasks, require a good task analysis in terms of frequency of movements or muscle activity. ***Relevance to industry:*** The effectiveness of job rotation in industrial environment is still controversial, namely in manual assembly tasks. Although, there was some evidence that rotation conditions had a positive effect on wrist muscle load. However, no consistent results were found through electromyography based measurements.

Keywords: job rotation, assembly work, wrist, muscle fatigue

6.1. Introduction

Work-related upper limb musculoskeletal disorders (WRULDs) have a great impact in workers' welfare contributing to absenteeism (Buckle & Jason Devereux, 2002; Punnett & Wegman, 2004; Stewart, Ricci, Chee, & Morganstein, 2003). Repetitive manual work is a risk factor associated with wrists and hands disorders, such as tendon-related disorders, carpal tunnel syndrome (CTS) and cramp of the hand and forearm (Hansson et al., 2000; Latko et al., 1999; Muggleton, Allen, & Chappell, 1999; Viikari-Juntura &

Silverstein, 1999). It was proved that women are more susceptible to CTS symptoms than man (Zetterberg & Öfverholm, 1999). In a recent survey, more than 60% of workers have reported that they perform repetitive hand or arm movements at work (Eurofound, 2012). Monotonous and repetitive work is common in current industry (Mathiassen, 2006) due the time-intensive production systems with standardized and short-cycle tasks. Therefore, these production systems typically have a little task variation that can lead to a reduction in periods of muscle rest (Bao, Winkel, Mathiassen, & Shahnavaz, 1997), increasing the risk of muscle fatigue. This way muscle fatigue can be used as a biomarker for predicting and preventing the development work-related musculoskeletal disorders (WRMSDs) (Madeleine, 2010; Marras & Karwowski, 2006). Physical variation has been proposed to minimize musculoskeletal injury risk and fatigue in jobs with repetitive tasks (Fallentin, Viikari-Juntura, Wærsted, & Kilbom, 2001; Kilbom, 1994; Konz, 1998; Kuijer, Visser, & Kemper, 1999). Job rotation (or "task rotation") is an intervention strategy to increase exposure variation. The general principle of job rotation consists in promoting alternating tasks in order to provide rest periods to the muscle groups and to reduce overall muscle activity, thus reducing muscular overload (Mathiassen, 2006). Raina & Dickerson (2009) showed that performing continuous shoulder abduction was more fatiguing than rotation between shoulder abduction and flexion. Wells, McFall, & Dickerson (2010) also demonstrated positive results of prehensile activity variation despite of the high functional similarity of tasks. On the contrary, Keir, Sanei, & Holmes (2011) found that upper erector spinae and forearm muscles did not benefit by rotating lifting and gripping tasks. Horton, Nussbaum, & Agnew (2012) found that rotation frequency and task order at higher exertion level presented an increase of electromyography (EMG) amplitude and a decrease of EMG mean power frequency (MPF). However, at lower exertion tasks the results were opposite to the expected. The implementation of job rotation has become a common practice in companies as a response to the growth in WRULDs but little scientific evidence supported the effectiveness of this administrative control (Aptel, Cail, Gerling, & Louis, 2008; Mathiassen, 2006).

Assembly line work involves forearm muscle exertion and extreme wrist postures. Fifteen muscles cross the wrist joint, however only five are responsible for the neuromuscular control of the position and movement of the wrist joint. This group includes flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), extensor carpi radialis longus (ECRL), extensor carpi radialis brevis (ECRB) and extensor carpi ulnaris (ECU) muscles (Bawa, Chalmers, Jones, Søgaard, & Walsh, 2000). The motor control is dependent of proprioceptive afferent feedback and can be affected by muscle fatigue. Currently, the experts define proprioception as a total integration of sensory, motor and central processes pertaining to joint stability (Lephart & Freddie, 2000). The joint position sense is included in the conscious proprioception and is defined as the ability to accurately reproduce a specific joint angle (Hagert, 2010). The sense of position is influenced by muscle command and muscle conditioning (Smith, Crawford, Proske, Taylor, & Gandevia, 2009; Winter, Allen, & Proske, 2005). In a real-life occupational setting, proprioceptive deficits caused by muscle fatigue may be an important initiating factor associated with the occurrence of WRMSDs (Björklund, Crenshaw, Djupsjöbacka, & Johansson, 2000). Vafadar, Côté, & Archambault (2012) found that position sense error at shoulder level (rotation angle) was significantly higher after fatigue.

This study investigated the effect of job rotation on wrist muscle fatigue among experienced assembly workers. Additionally, considering the hypothesis that muscle fatigue leads to proprioceptive deficits and, consequently, it may be a contributing factor to the development of WRMSDs, was analyzed how muscle fatigue affected wrist position sense acuity.

6.2. Materials and Methods

The present field study was conducted in a company that produces different kinds of mechanical cables for the automotive industry. This company has implemented the Lean Production System (LPS) and assembly lines constitute most of the production area. The company has three fixed shifts (morning: 6:00 a.m.-14:00 p.m. (A); afternoon: 14:00 p.m.-22:00 p.m. (B); night: 22:00 p.m.-6:00 a.m. (C)). Each shift has one break of fifteen minutes. The selected assembly lines comprised five workstations, producing the same family products.

6.2.1. Participants

Sixteen female healthy volunteers (age: 26.00±4.79 years; stature: 156.34±5.08 cm; weight: 54.04±04 kg; body mass index: 22.03±2.13) participated in this study. To evaluate the effect of job rotation, three groups were selected: group 1 (G1) was constituted by four assembly workers rotating between five workstations at two hour intervals (rotation conditions) (see Table 1), group 2 (G2) was constituted by four workers that worked always in the same workstation (no rotation conditions) – workstation B - and, finally, the control group - group 3 (G3) – was composed of eight female volunteers from the university population (non exposed group). All participants were right-handed and the workers had over than 12 months of work experience. The study was performed after obtaining informed consent approved by the School of Allied Health Technologies, Polytechnic Institute of Porto Ethics Committee from each subject.

6.2.2. Work stations

In all workstations, workers adopted standing static postures using the upper limbs to place the materials in the equipment and to press the control buttons. Intensity level of this type of work activity is considered below than 20% of maximal voluntary contraction (MVC) in terms of median EMG amplitudes (Westgaard, Jansen, & Jensen, 1996), with highly repetitive movements of the wrist. Table 10 presents a description of work developed in the work stations of the production lines.

Table 10. Description of work stations.

Workstation	Task	Work method	Task time (s)
A	Lubricate and assemble outer tube in the conduit	1. Insert the conduit in the lubrication equipment ; 2. Hold the outer tube; 3. Place the lubricate conduit in the equipment; 4. Place the outer tube in the equipment; 5. Give command to the equipment assemble all the materials.	5
B	Assemble and press terminals of the conduit	1. Hold component; 2. Place component in the extremity of the conduit; 3. Place the subset in the equipment; 4. Hold component; 5. Place the component in the extremity of the conduit; 6. Give command to the equipment.	5.5
C	Assemble cable in the conduit and cut the edge of the cable	1. Hold the subset; 2. Place the subset in the equipment; 3. Hold the cable; 4. Give command at the equipment.	5
D	Press second cable terminal	1. Place the subset in the equipment; 2. Hold the cable terminal; 3. Give command to the equipment.	6.7
E	Rehearsal and recording ink into the final product	1. Hold de subset; 2. Place the subset in the equipment; 3. Give command to the equipment.	6

6.2.3. Experimental procedure and instrumentation

<u>Data acquisition</u>

Data were collected on Monday (before the beginning of the work week) and on Friday (after the end of the work week). To control the disturbances in the production, all assembly workers completed a written record (log book). No considerable differences in the production volumes were observed and workers followed the work station rotation system. G3 was evaluated in the same conditions.

<u>Position sense test</u>

Participants were seated in an ajustable chair and placed their right arm on the armpad, allowing flexion-extension movements about the right wrist joint while keeping the lower arm fixed at 90°of elbow flexion. A twin-axis Goniometer 110 (model Biopac TSD130A) was used to measure wrist angular movement. The goniometer was connected directly to a Biopac DA100C amplifier and gain was set to 1000. The sampling frequency was 200 Hz and data were collected and analyzed using AcqKnowlegde 4.1 for Mac OS X (BIOPAC Systems Inc, Santa Barbara, CA USA). The goniometer was fixed with adhesive tape. The reference position of the wrist (0° of wrist flexion and extension) was recorded with the forearm and hand in a neutral position. The starting position was always the reference position and the target position was 45º of wrist extension and flexion (Figure 13).

a) **b)** **c)**

Figure 13. Joint position sense tests: (a) neutral position; b) flexion (45º); c) extension (45º).

Initially, the joint position sense test was trained with visual cues for the subjects to feel comfortable in the experimental setting. Then, and already blindfolded, their hand was actively moved from the reference position to the target position at an angular velocity around 45º.s^{-1} and remained at this position during 5 s. Next, the subjects actively moved the wrist between reference position and target position, according to the instructions. When they considered the wrist to be at the target position, they gave an oral indication to the investigator responsible to register the moment in the computer. Six trials were performed for each movement of the wrist. The initial direction of movement was alternated between days and subjects. To evaluate the magnitude of the position error, the absolute error of the joint angle (defined as the absolute difference between the memorized angle and the reproduced angle) was calculated.

Electromyography recordings

After joint position sense tests, electromyography from the extensor carpi radialis muscle (ECR) and the flexor carpi radialis muscle (FCR) was measured by a BIOPAC MP100 System and amplified with EMG100C modules (BIOPAC Systems Inc, Santa Barbara, CA USA) during an isometric test contraction with a duration of 180 s at 15% of the MVC using a hand dynamometer (BIOPAC TSD121C). The selected muscles cooperate to perform prehensile activities and to stabilize the wrist. The grip selected for trials was pinch grip due to their predominance during assembly tasks. Raw EMG signals were sampled during the test contraction with a sample frequency of 1000 Hz and band-pass filtered (20–500 Hz). All EMG analyses were performed using AcqKnowlegde 4.1 for Mac OS X (BIOPAC Systems Inc., Santa Barbara, CA USA). During trials, each participant was sitting upright with their feet on the floor, and their knees at 90º, while their shoulders were parallel to the floor and their forearms were flexed (105º) horizontally and supported, with the forearm and wrist in a neutral position. Forearm skin surfaces were prepared with an abrasive gel (Nuprep Skin Prep Gel) followed by application of an alcohol in order to reduce electrical resistance to less than 5000 Ω. Skin impedance was measured using the Noraxonr® Impedance Checker system (Noraxon, Scottsdale, Arizona). Bipolar surface electrodes (Ag/AgCl, wet gel, Dormo) were placed with an inter-electrode distance of 20 mm (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). The electrodes were placed in the following manner: a) FCR – one third of the distance from the proximal end of a line from the medial epicondyle to the distal head of the radius; ECR – two fingerbreadths distal to the lateral epicondyle (Mogk & Keir, 2003b). Ground electrodes were placed over both olecraneums (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). Before applying electrodes, the muscle belly location was confirmed by palpation during muscle-specific movements of the wrist.

EMG data analysis

Root mean square (RMS) amplitude values were normalized to the EMG values measured during the maximal handgrip strength at the start of the week. RMS was extracted from time domain of the rectified signals. The signals were then smoothed by means of a moving RMS window (time window 100 ms). Median frequency (MF) of the EMG power spectrum was calculated in each 1 s interval with fast Fourier transforms (FFT). Linear regression analysis was performed on RMS and MF as a function of time. The slope of the MF regression line was normalized by ($NMF_{slope}= \frac{MFslope}{MFinit} \times 100\%$), according to Coorevits, Danneels, Cambier, Ramon, & Vanderstraeten (2008), due to the potential differences subcutaneous layers between subjects and between different muscles of the subject. The initial median frequency (MF_{init}) was defined as the intercept of the regression line, and the median frequency slope (MF_{slope}) was determined as the slope of the regression line. The negative slope of the regression line of MF is commonly used as an indicator of the muscle's fatigability (Hägg, Luttmann, & Jäger, 2000; Luttmann, Jäger, Sökeland, & Laurig, 1996). However, the positive slope of the regression line of RMS is interpreted as an indicator of fatigue (Luttmann et al., 1996).

6.2.4. Statistical analysis

Statistical analyses were performed in SPSS 22.0 (SPSS Inc., Chicago, IL, USA). T-tests for paired samples were used to verify if there were any differences between EMG parameters of the wrist muscles in each measured moment. Additionally, a repeated measures two-way analysis of variance (ANOVA) was used to determine differences between EMG parameters before and after work, as well as between groups. *P*-Values were based on the degrees of freedom corrected with Greenhouse-Geisser's epsilon. Statistical significance was accepted at $p<0.05$.

6.3. Results

6.3.1. EMG measurements

Figure 14 shows the normalized regression coefficient of the median frequencies (NMF_{slope}) values for FCR and ECR muscles and groups under study. Overall, G1 had higher (less negative) NMF_{slope} values than G2 for both muscles, indicating less fatigue. G1 showed significant higher NMF_{slope} values for FCR than for ECR (p=0.039) at the beginning of the week, that represent less fatigue for this muscle. On the contrary, G2 showed significant lower NMF_{slope} values for FCR than ECR at the end of the work week (p=0.004). However, the repeated measures ANOVA did not reveal any effects of rotation conditions (p=0.454) or time (p=0.219). RMS slope values of FCR showed an increase after a week in the three groups (Figure 15). RMS slope values of G3 were significant higher for FCR than ECR in the last evaluation (p=0.032). Statistical analysis did not found significant differences for RMS slope values between groups (p=0.903) on the two measuring moments (p=0.218).

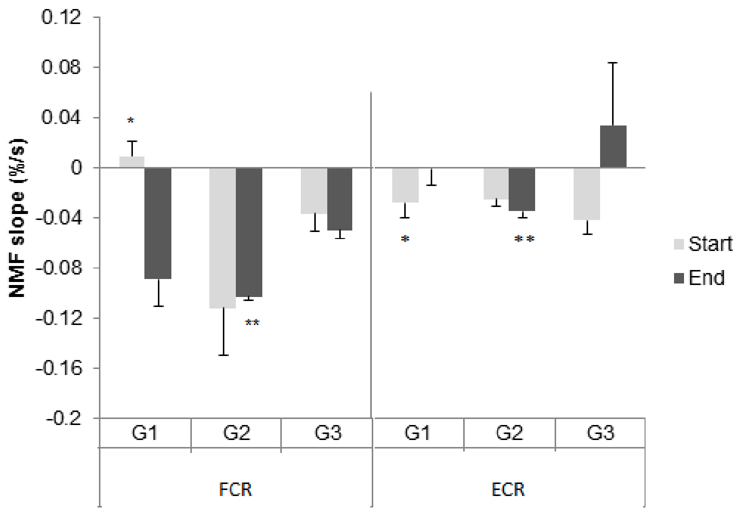


Figure 14. NMFslope values (%/s) of flexor carpi radialis (FCR) and extensor carpi radialis (ECR) muscles. Data are expressed as the means ± standard error of the mean. G1 – rotation conditions (n=4); G2 - no rotation conditions (n=4); G3 - non exposed group (n=8). *Significant difference between FCR and ECR (p=0.039); **Significant difference between FCR and ECR (p=0.004)

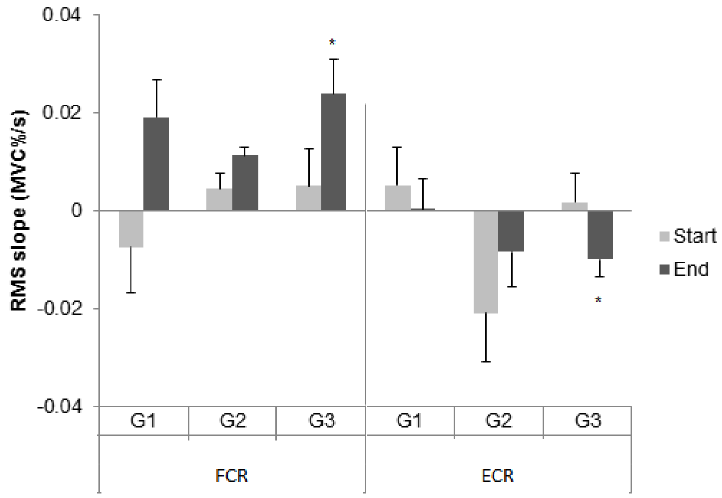


Figure 15. RMS slope values (MVC%/s) of flexor carpi radialis (FCR) and extensor carpi radialis (ECR) muscles. Data are expressed as the means ± standard error of the mean. G1 – rotation conditions (n=4); G2 - no rotation conditions (n=4); G3 - non exposed group (n=8).*Significant difference between FCR and ECR (p=0.032).

6.3.2. Position sense test

Figure 16 and 17 shows absolute errors (degrees) for the three groups at the beginning and at the end of the week. Absolute error increased after a week in the direction of wrist flexion (see Figure 16). G2 had higher absolute error (6.08±4.26) than G1 (4.61±3.14) and G3 (4.92±2.92) for flexion in the initial measurement. However, G1 showed a greater increase in errors after a work week (7.19±6.78). On the contrary, the absolute errors for extension have a decrease after a week for all groups (see Figure 17). Additionally, the repeated measures ANOVA revealed that variance on absolute error are independent of the experimental group (p=0.798) or time (p=0.102). Hence, wrist position sense did not change due to the exposure to assembly work. Despite the G2 demonstrated higher error than G1, statistical analysis did not reveal any effects of rotation schemes on the exposure groups.

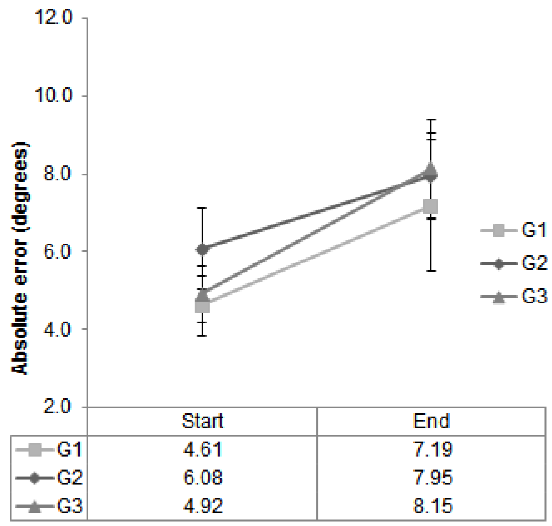


Figure 16. Absolute errors (degrees) between target and matching positions before work and after a work week for wrist flexion. G1 – rotation conditions (n=4); G2 - no rotation conditions (n=4); G3 - non exposed group (n=8). Data are expressed as the means ± standard error of the mean.

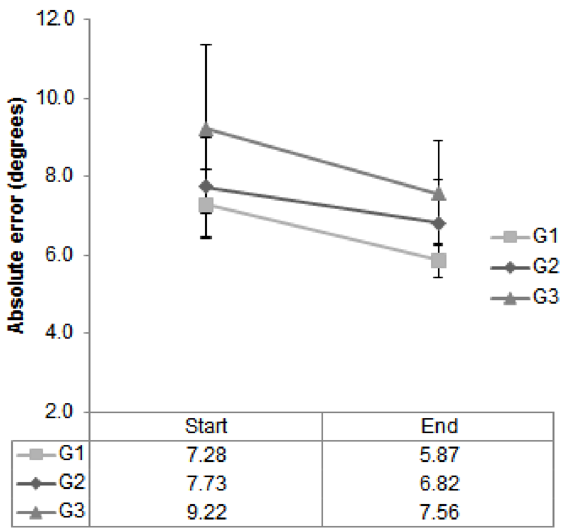


Figure 17. Absolute errors (degrees) between target and matching positions before work and after a work week for wrist extension. G1 – rotation conditions (n=4); G2 - no rotation conditions (n=4); G3 - non exposed group (n=8). Data are expressed as the means ± standard error of the mean.

6.4. Discussion

Overall, our results showed different trends for EMG parameters of FCR and ECR in each group. During test contraction, at the beginning of the week, G1 seems to have started a fatigue process in the ECR muscle; in turn G2 presented EMG manifestations of muscle fatigue for the FCR muscle. After a week, G1 and G2 showed signs of fatigue in the same muscle – the FCR. These results were consistent with those obtained in the position sense test, where there was a trend for increased of absolute error in the direction of wrist flexion after a work week. The G3 revealed similar results of the exposure group, showing a greater decline of NMF_{slope} and an increase of RMS slope value at the end of week, which is an indicator of fatigue (Luttmann et al., 1996) for the FCR muscle. Considering these results, the FCR seems to have benefited by rotating between assembly tasks. In fact, the G2 showed EMG signs of fatigue of FCR before and after the work week, which can be related to the continuous recruitment of this muscle in the same work station (accumulated fatigue). Although the results obtained in this study show a tendency, in general there were no statistically significant differences between EMG parameters of the wrist muscles that have been studied. On the other hand, when comparing muscle groups involved in the movement of different joints, such as upper trapezius and forearm extensors, there was found that the latter showed less work load variability than upper trapezius during rotation between workstations in cyclic assembly work (Möller, Mathiassen, Franzon, & Kihlberg, 2004). Keir et al. (2011) found that upper erector spinae and forearm muscles did not benefit by rotating lifting and gripping tasks. Other study carried out by Crenshaw, Djupsjöbacka, & Svedmark (2006) found that work time and pauses (active vs passive) did not significantly affect EMG median frequency and EMG amplitude of extensor carpi radialis muscle as well as wrist position sense during computer mouse work. Horton, Nussbaum, & Agnew (2014) also found no consistent effects of task order when rotating between lifting tasks of different intensity levels. In turn, Björklund et al. (2000) found that position sense acuity of shoulder decreased following a simulated repetitive low-intensity work task to fatigue. Assembly work is associated with intense use of forearm muscles and wrist. Therefore, the implementation of job rotation or enlargement in assembly line work is quite challenging due to the difficulty of to find alternative tasks to provide rest periods to different muscle groups, reducing muscular overload (Mathiassen, 2006; Wells et al., 2010).

Some factors may have influenced the changes of EMG parameters of muscles under study. Bennie, Ciriello, Johnson, & Dennerlein (2002) recognized that physiological change of muscle tissue and alterations in the balance of force between synergistic muscles resulting from learning and coordination effects can change the EMG power spectra. Some authors (Bonnard, Sirin, Oddsson, & Thorstensson, 1994; Cote, Feldman, Mathieu, & Levin, 2008; Fuller, Lomond, Fung, & Côté, 2009; Vafadar et al.,

2012) reported that in the presence of muscle fatigue, subjects can use compensation strategies, involving more joints and muscles, to perform a specific task. However, in the present experiment, only the EMG signal of FCR and ECR muscles has been recorded. The crosstalk phenomenon is known to influence the EMG power spectrum due the close proximity of forearm muscles and their small surface area (Mogk & Keir, 2003) Additionally, it is important to note that in the experimental design the last measurement (on Friday) of muscle EMG activity and position sense tests was performed after a long rest period, which could have influenced the obtained results. Some factors related to protocol design and equipment can affect the results of joint position sense tests. Goble (2010) identified experimental factors that should be considered in the assessment of proprioceptive acuity, such as the suitability of reference position established to experimental group and the type of position matching task. Considering the obtained results, the matching performance of the sample should have been tested. The electrogoniometer shown to be adequate to the experimental conditions (field experiment) due to its portability, easy application (Rowe, Myles, Hillmann, & Hazlewood, 2001) and reliability for wrist motion assessment (Camassuti et al., 2015).

Some limitations were present in this field study that should be noted. Despite the job rotation schemes have been fulfilled by workers, factors such as production breaks may have increased the recovery periods during the week. Small sample size and inter-subject variability may also have influenced the effects of rotation. Moreover, the sEMG-based estimation of force and fatigue has limitations related to the muscle conduction velocity and recruitment pattern (Gazzoni, 2010; Sood, Nussbaum, & Hager, 2007; Yassierli & Nussbaum, 2008). Other important muscle physiological changes that result from repetitive work of low load, could have been monitored including muscle oxygenation (Crenshaw et al., 2006), metabolic products and muscle mechanical properties (excitation-contraction coupling) (Bosch, de Looze, & van Dieën, 2007).

6.5. Conclusions

Overall, the results of this study suggest that no significant benefits of job rotation were evident in terms of EMG signs of muscle fatigue and wrist position sense. However, it would be important to study a larger sample and collect objective and subjective indicators of fatigue. The work in assembly lines require a continuous recruitment of forearm muscles, thus the implementation of a rotation system should consider alternating between tasks with different frequency of movements or muscle activity.

6.6. References

Aptel, M., Cail, F., Gerling, A., & Louis, O. (2008). Proposal of parameters to implement a workstation rotation system to protect against MSDs. *International Journal of Industrial Ergonomics*, *38*(11-12), 900–909.

Bao, S., Winkel, J., Mathiassen, S. E., & Shahnavaz, H. (1997). Interactive effect of ergonomics and production engineering on shoulder- neck exposure - A case study of assembly work in China and Sweden. *International Journal of Industrial Ergonomics*, *20*(1), 75–85.

Bawa, P., Chalmers, G. R., Jones, K. E., Søgaard, K., & Walsh, M. L. (2000). Control of the wrist joint in humans. *European Journal of Applied Physiology*, *83*(2-3), 116–127.

Bennie, K. J., Ciriello, V. M., Johnson, P. W., & Dennerlein, J. T. (2002). Electromyographic activity of the human extensor carpi ulnaris muscle changes with exposure to repetitive ulnar deviation. *European Journal of Applied Physiology*, *88*(1-2), 5–12.

Björklund, M., Crenshaw, A. G., Djupsjöbacka, M., & Johansson, H. (2000). *Position sense acuity is diminished following repetitive low-intensity work to fatigue in a simulated occupational setting. European journal of applied physiology*, *81*(5), 361–367).

Bonnard, M., Sirin, A. V., Oddsson, L., & Thorstensson, A. (1994). Different strategies to compensate for the effect of fatigue revealed by neuromuscular adaptation processes in humans. *Neuroscience Letters*, *166*(1), 101–105.

Bosch, T., de Looze, M. P., & van Dieën, J. H. (2007). Development of fatigue and discomfort in the upper trapezius muscle during light manual work. *Ergonomics*, *50*(2), 161–177.

Buckle, P. W., & Jason Devereux, J. (2002). The nature of work-related neck and upper limb musculoskeletal disorders. *Applied Ergonomics*, *33*(3), 207–217.

Camassuti, P. A. da S., Marcolino, A., Tamanini, G., Barbosa, R. I., Barbosa, A. M., & de Cássia Registro Fonseca, M. (2015). Inter-rater, intra-rater and inter-instrument reliability of an electrogoniometer to measure wrist range of motion. *Hand Therapy*, *20*(1), 3-10.

Coorevits, P., Danneels, L., Cambier, D., Ramon, H., & Vanderstraeten, G. (2008). Assessment of the validity of the Biering-Sørensen test for measuring back muscle fatigue based on EMG median frequency characteristics of back and hip muscles. *Journal of Electromyography and Kinesiology*, *18*(6), 997–1005.

Cote, J. N., Feldman, A. G., Mathieu, P. A., & Levin, M. F. (2008). Effects of fatigue on intermuscular coordination during repetitive hammering. *Motor Control*, *12*(2), 79–92.

Crenshaw, A. G., Djupsjöbacka, M., & Svedmark, A. (2006). Oxygenation, EMG and position sense during computer mouse work. Impact of active versus passive pauses. *European Journal of Applied Physiology*, *97*(1), 59–67.

Eurofound. (2012). *Fifth European Working Conditions Survey*. Luxembourg: Publications Office of the European Union.

Fallentin, N., Viikari-Juntura, E., Wærsted, M., & Kilbom, Å. (2001). Evaluation of physical workload standards and guidelines from a Nordic perspective. *Scandinavian Journal of Work, Environment and Health*, *27*(Suppl. 2), 1–52.

Fuller, J. R., Lomond, K. V., Fung, J., & Côté, J. N. (2009). Posture-movement changes following repetitive motion-induced shoulder muscle fatigue. *Journal of Electromyography and Kinesiology*, *19*(6), 1043–1052.

Gazzoni, M. (2010). Multichannel surface electromyography in ergonomics: Potentialities and limits. *Human Factors and Ergonomics In Manufacturing*, *20*(4), 255–271.

Goble, D. J. (2010). Proprioceptive acuity assessment via joint position matching: from basic science to general practice. *Physical Therapy*, *90*(8), 1176–1184.

Hagert, E. (2010). Proprioception of the Wrist Joint: A Review of Current Concepts and Possible Implications on the Rehabilitation of the Wrist. *Journal of Hand Therapy*, *23*(1), 2–17.

Hägg, G. M., Luttmann, A., & Jäger, M. (2000). Methodologies for evaluating electromyographic field data in ergonomics. *Journal of Electromyography and Kinesiology*, *10*(5), 301-312.

Hansson, G. Å., Balogh, I., Ohlsson, K., Pålsson, B., Rylander, L., & Skerfving, S. (2000). Impact of physical exposure on neck and upper limb disorders in female workers. *Applied Ergonomics*, *31*(3), 301–310.

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology*, *10*(5), 361–374.

Horton, L. M., Nussbaum, M. A., & Agnew, M. J. (2012). Effects of rotation frequency and task order on localised muscle fatigue and performance during repetitive static shoulder exertions. *Ergonomics*, *55*(10), 1205-1217.

Horton, L. M., Nussbaum, M. A., & Agnew, M. J. (2014). Rotation During Lifting Tasks: Effects of Rotation Frequency and Task Order on Localized Muscle Fatigue and Performance. *Journal of Occupational and Environmental Hygiene*, *12*(2), 95–106.

Keir, P. J., Sanei, K., & Holmes, M. W. R. (2011). Task rotation effects on upper extremity and back muscle activity. *Applied Ergonomics*, *42*(6), 814–819.

Kilbom, Å. (1994). Repetitive work of the upper extremity: Part I—Guidelines for the practitioner. *International Journal of Industrial Ergonomics*, *14*(1-2), 51–57.

Konz, S. (1998). Work/rest: Part II - The scientific basis (knowledge base) for the guide. *International Journal of Industrial Ergonomics*, *22*(1-2), 73-99.

Kuijer, P. P., Visser, B., & Kemper, H. C. (1999). *Job rotation as a factor in reducing physical workload at a refuse collecting department. Ergonomics*, *42*(9), 1167–1178).

Latko, W. A., Armstrong, T. J., Franzblau, A., Ulin, S. S., Werner, R. A., & Albers, J. W. (1999). Cross-sectional study of the relationship between repetitive work and the prevalence of upper limb musculoskeletal disorders. *American Journal of Industrial Medicine*, *36*(2), 248–259.

Lephart, S. M., & Freddie, H. F. (2000). *Proprioception Control in Joint Stability* (1st ed., p. 439). Champaign, IL: Human Kinetics.

Luttmann, A., Jäger, M., Sökeland, J., & Laurig, W. (1996). Electromyographical study on surgeons in urology. II. Determination of muscular fatigue. *Ergonomics*, *39*(2), 298–313.

Madeleine, P. (2010). On functional motor adaptations: From the quantification of motor strategies to the prevention of musculoskeletal disorders in the neck-shoulder region. *Acta Physiologica*, *199* (Suppl. 679), 1–46.

Marras, W. S., & Karwowski, W. (2006). *Fundamentals and Assessment Tools for Occupational Ergonomics* (2nd ed., p. 1024). Boca Raton: CRC Press.

Mathiassen, S. E. (2006). Diversity and variation in biomechanical exposure: What is it, and why would we like to know? *Applied Ergonomics*, *37*(4), 419–427.

Mogk, J. P. M., & Keir, P. J. (2003). The effects of posture on forearm muscle loading during gripping. *Ergonomics*, *46*(9), 956–975.

Möller, T., Mathiassen, S. E., Franzon, H., & Kihlberg, S. (2004). Job enlargement and mechanical exposure variability in cyclic assembly work. *Ergonomics*, *47*(1), 19–40.

Muggleton, J. M., Allen, R., & Chappell, P. H. (1999). Hand and arm injuries associated with repetitive manual work in industry: a review of disorders, risk factors and preventive measures. *Ergonomics*, *42*(5), 714–739.

Punnett, L., & Wegman, D. H. (2004). Work-related musculoskeletal disorders: the epidemiologic evidence and the debate. *Journal of Electromyography and Kinesiology*, *14*(1), 13–23.

Raina, S. M., & Dickerson, C. R. (2009). The influence of job rotation and task order on muscle fatigue: A deltoid example. *Work: a Journal of Prevention Assessment & Rehabilitation, 34*(2), 205-213.

Rowe, P., Myles, C., Hillmann, S., & Hazlewood, M. (2001). Validation of Flexible Electrogoniometry as a Measure of Joint Kinematics. *Physiotherapy*, *87*(9), 479-488.

Smith, J. L., Crawford, M., Proske, U., Taylor, J. L., & Gandevia, S. C. (2009). Signals of motor command bias joint position sense in the presence of feedback from proprioceptors. *Journal of Applied Physiology*, *106*(3), 950–958.

Sood, D., Nussbaum, M. A., & Hager, K. (2007). Fatigue during prolonged intermittent overhead work: reliability of measures and effects of working height. *Ergonomics*, *50*(4), 497–513.

Stewart, W. F., Ricci, J. A., Chee, E., & Morganstein, D. (2003). Lost productive work time costs from health conditions in the United States: results from the American Productivity Audit. *Journal of Occupational and Environmental Medicine*, *45*(12), 1234–1246.

Vafadar, A. K., Côté, J. N., & Archambault, P. S. (2012). The effect of muscle fatigue on position sense in an upper limb multi-joint task. *Motor Control*, *16*(2), 265–83.

Viikari-Juntura, E., & Silverstein, B. (1999). Role of physical load factors in carpal tunnel syndrome. *Scandinavian Journal of Work, Environment and Health*, *25*(3), 163–185.

Wells, R., McFall, K., & Dickerson, C. R. (2010). Task selection for increased mechanical exposure variation: relevance to job rotation. *Ergonomics*, *53*(3), 314–323.

Westgaard, R.H., Jansen, T., & Jensen, C. (1996). EMG of the neck and shoulder muscles: the relationship between muscle activity and muscle pain in occupational settings. In S. Kumar and A. Mital (Ed.), *Electromyography in ergonomics.* (pp. 227–258). London: Taylor and Francis.

Winter, J. A., Allen, T. J., & Proske, U. (2005). Muscle spindle signals combine with the sense of effort to indicate limb position. *Journal of Physiology*, *568*(3), 1035–1046.

Yassierli, & Nussbaum, M. A. (2008). Utility of traditional and alternative EMG-based measures of fatigue during low-moderate level isometric efforts. *Journal of Electromyography and Kinesiology*, *18*(1), 44–53.

Zetterberg, C., & Öfverholm, T. (1999). Carpal tunnel syndrome and other wrist/hand symptoms and signs in male and female car assembly workers. *International Journal of Industrial Ergonomics*, *23*(3), 193–204.

CHAPTER 7: Influence of automation on biomechanical exposure of the upper-limbs in an industrial assembly line: application of a wireless inertial motion capture system under field conditions

Abstract

Automation of assembly work was originally developed in order to increase operation efficiency and at same time, reducing workload. However, a considerable number of unanticipated ergonomic problems have been observed such as the interaction between humans and automated systems. The aims of this field study were to quantify joint angle positions (shoulder, elbow and wrist) of workers in two assembly lines with different mechanization levels and analyse the performance of an inertial motion capture system. Seven experienced female assemblers participated in this study. The measurements were performed in workplace with a full-body inertial measurement system (Xsens MVN BIOMECH system). Maximum cross-correlation between angle-time courses was calculated to quantify the waveform similarities. In manual line there are larger variations of joint angles than in the semi-automatic one. The analysis of cross correlation coefficients revealed that electromagnetic interferences are potential limitations to the use of these systems under field conditions.

Keywords: assemble work, joint angular kinematics, automation, inertial motion capture, upper-limb.

7.1. Introduction

The major challenge for ergonomics is to design the work in order to prevent work-musculoskeletal disorders (WMSDs) without negative impact on production quality and productivity (Wells, Mathiassen, Medbo, & Winkel, 2007). However, WMSDs are still prevalent across Europe and have a great impact in the quality of life of the workers (Eurofound, 2012). In fact, work organization has been changing through the years mostly due to technological advances, legal and political changes and competiveness among companies. The growth of mass production and automated technologies led to the emergence of new ergonomic problems due to work intensification (Coury, Alfredo Léo, & Kumar, 2000). This trend in contemporary manufacturing industries is associated with the selection of serial or parallel flow production strategies and the reduction of waste in the production system (rationalization) (Palmerud, Forsman, Neumann, & Winkel, 2012; Westgaard & Winkel, 2011). According to a systematic review carried out by Westgaard & Winkel (2011), rationalization of production had a great impact on musculoskeletal and mental health of the workers. They also recognized that more research on ergonomic intervention is needed to understand the prerequisites of sustainable production systems (balance between production performance and worker wellbeing). Assembly lines are flow-oriented production systems developed to achieve, in a more efficient way, higher production rates of standardized products (Boysen, Fliedner, & Scholl, 2007). Several authors investigated new methods to optimize assembly systems, disregarding ergonomic issues (Battini, Faccio, Ferrari, Persona, & Sgarbossa, 2007; Toksari, Işleyen, Güner, & Baykoç, 2008; Wei & Chao, 2011; Yeh & Kao, 2009). However, assembly tasks are characterized by strictly standardized procedures with short cycle times (less than 30s), little task variation, repetitive movements and reduced breaks or pauses which supports the importance of integrating ergonomic approaches in the design of these production systems (Battini et al., 2007; Neumann, Winkel, Medbo, Magneberg, & Mathiassen, 2006). The automation level of assembly processes may have implications on physical workload. Neumann, Kihlberg, Medbo, Mathiassen & Winkel (2002) reported that the automation of assembly work and transport in production lines increased productivity and reduce mechanical load on operators. A comparative study carried out by Wong & Richardson (2010), showed that the operators had more complaints associated to musculoskeletal pain while working in a Lean Production Line (technologically advanced) than in a Conventional one.

Assessment of physical exposures (e.g. joint kinematics and kinetics) is important for understanding the risk of WMSDs and defines ergonomic interventions (Qin, Lin, Faber, Buchholz, & Xu, 2014). Currently some authors consider that quantification of physical exposure in work environment is essential due to the influence of organizational factors or physical constrains in working procedures (Garg & Kapellusch, 2009; Marras, Cutlip, Burt, & Waters, 2009). Recent motion capture systems enable a detailed analysis of tasks, allowing ergonomic improvements in the production system design. However, considering the three-dimensional (3D) systems, they reveal some limitations related to the complexity and space requirements (e.g. Vicon Motion Systems; Los Angeles, California) or accuracy when applied in the field. Inertial measurement systems (e.g. Xsens; Enschede, Netherlands) are a possible alternative for portable 3-D motion capture to carry out evaluations in the work environment. Besides requiring less space, they are low-cost and fully wearable motion analysis systems (Cutti, Giovanardi, Rocchi, Davalli, & Sacchetti, 2008).

The present study was conducted at a multinational corporation devoted to the production of mechanical cables for automotive industry. This company has implemented the Lean Production System (LPS) and assembly lines constitute the most of production area. The automation/mechanization of assembly processes has been modified to improve production efficiency and ergonomic conditions. Accordingly, the aim of this field study is to quantify differences in the upper-limb mechanical exposure between the two assembly lines with different mechanization levels. Considering the importance of examined the ability of inertial motion capture system in realist conditions, it was evaluated the application and performance of this system.

7.2. Methods and Materials

7.2.1. Production system design

The production systems studied consisted of two assembly lines: the manual and the semi-automated line. The manual production line is the oldest one. Both assembly lines have *andon* and *poke-yoke* systems, so all problems are immediately reported (maintenance, quality and components supply). Moreover, these lines are producing the same product – automobile door cables. At the beginning of each shift, the operator carries out a thorough check of the main of the cable quality. Every two hours a product quality verification takes place. Other controls are also made by each operator such as: a) safety items, i.e., all the equipment has its safety protections placed and they must be are operative; b) 5S (workplace organization), i.e., cleaning and organization of the workstation. The company has three fixed shifts (morning: 6:00-14:00; afternoon: 14:00-22:00; night: 22:00-6:00). Each shift has a break of fifteen minutes.

The manual line included six workstations with a parallel configuration (Figure 18). The Workstations M1 and M2 are performed by the same operator. The operator presses the control buttons after completing each subset. The subsets are transported through each workstation by a drag mat. In the case of the semi-automated line only three operators assemble the cables (Figure 19). “Lubricate conduit”, “press second cable terminal” and “rehearsal and recording ink into the final product” are automated processes in semi-automated line. The structure of the lines is different due the automation of some operations. The Workstations A1 and A2 are performed by the same operator. The packing task was not considered in this study. Table 11 shows a description of both lines in terms of tasks and time cycle.

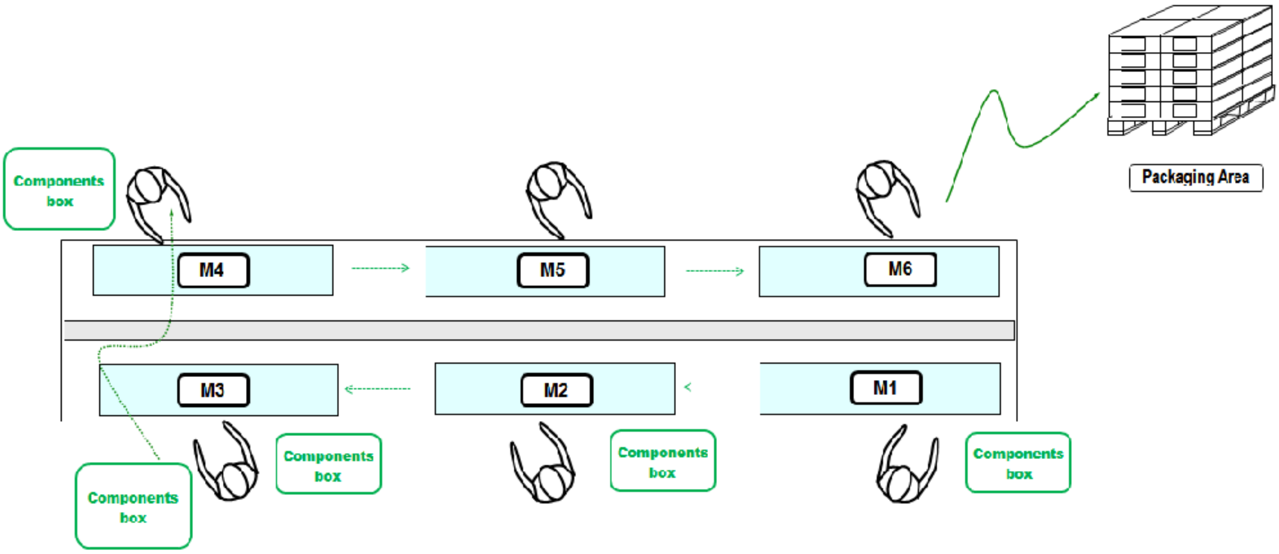


Figure 18. Layout of manual line.

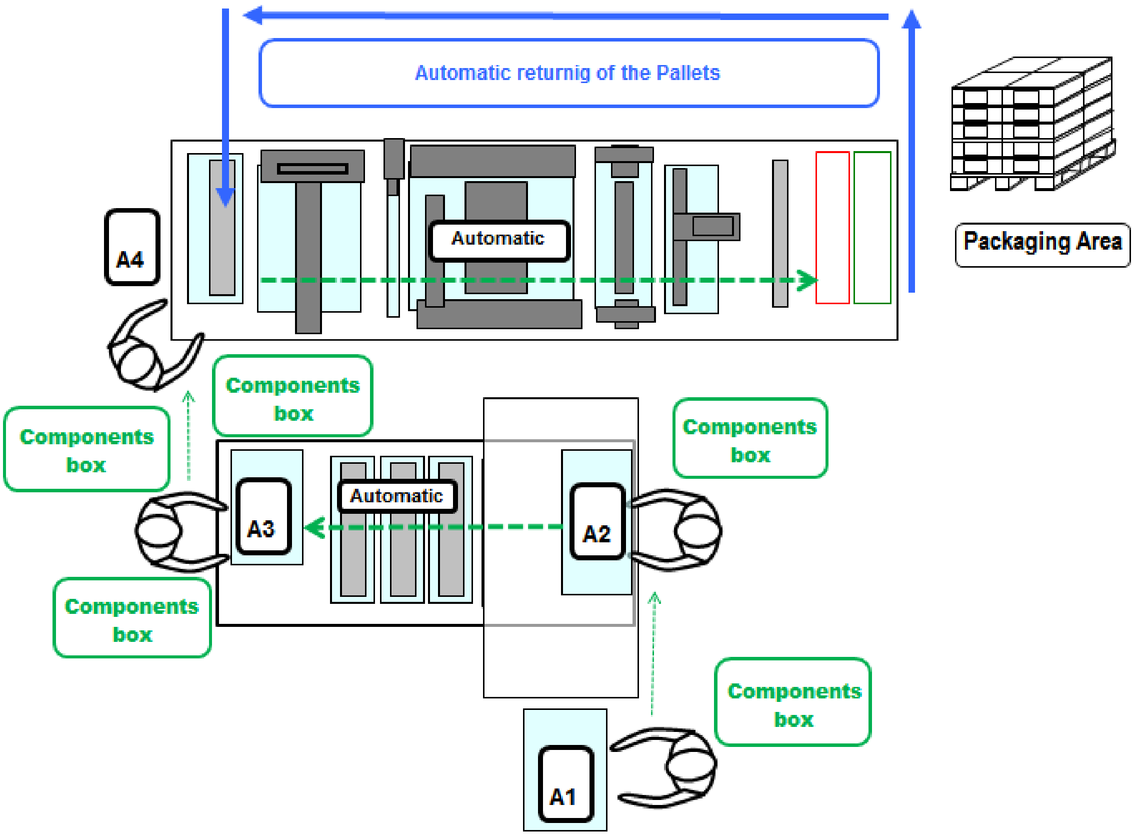


Figure 19. Layout of semi-automated line.

Table 11. Characteristics of the manual and semi-automated production lines (n=7).

	Workstation	Task	Cycle Time
Manual Line			
	M1	Ream the extremity of conduit	1 (per conduit)
	M2	Lubricate and assemble outer tube in the conduit	5
	M3	Assemble and press terminals of the conduit	5.5
	M4	Assemble the cable in the conduit and cut the edge of the cable	5
	M5	Press second cable terminal	6.7
	M6	Rehearse and record ink into the final product	6
Semi-automated Line			
	A1	Ream the extremity of conduit	1 (per conduit)
	A2	Assemble the outer tube in the conduit and place the subset in the automatic pallet of the equipment	5.5
	A3	Assemble and press terminals of the conduit	5.5
	A4	Assemble cable in the conduit	6.7

7.2.2. Subjects

Seven experienced female assemblers were selected to participate in this field study. All workers belonged to the afternoon shift and were right-handed. Their average age was 37.3 years old (range: 24-55 years) with 5.7 years (range: 1-14 years) of working experience. The participants signed an informed consent approved by the School of Allied Health Technologies, Polytechnic Institute of Porto Ethical Committee. None of the subjects reported any pain or musculoskeletal disorders. Table 12 shows anthropometric and body composition data of the sample.

Table 12. Anthropometric data and body composition of the sample.

		Manual Line	Semi-automated Line
Anthropometric Data (Standing)	Stature (cm)	161.55 (± 6.36)	155.00 (± 3.91)
	Eye height (cm)	149.54 (± 6.17)	145.02 (± 4.50)
	Shoulder height (cm)	134.14 (± 5.31)	129.08 (± 3.75)
	Elbow Height (cm)	103.25 (± 5.15)	98.02 (± 2.05)
	Wrist height (cm)	71.09 (± 3.62)	68.95 (± 2.86)
	Shoulder breadth (bi-deltoid) (cm)	42.75 (± 2.98)	41.77 (± 3.72)
	Elbow-wrist distance (cm)	31.11 (±1.90)	29.85 (± 0.46)
	Forward Reach (cm)	66.19 (± 2.78)	63.73 (±1.34)
Body Composition*	Weight (Kg)	59.68 (± 9.76)	52.75 (±11.10)
	Skeletal Muscle Mass (Kg)	22.35 (± 1.69)	21.40 (± 2.83)
	Body Fat Mass (Kg)	17.98 (± 1.44)	16.85 (± 1.20)
	Body Fat Percentage (%)	29.83 (± 8,78)	24.75 (± 6.01)
	Body Mass Index (BMI)	22.95 (± 4,18)	21.45 (± 3.04)

*Body composition was determined by bioelectrical impedance analysis (BIA).

7.2.3. Data collection procedure and instrumentation

Upper limb movements (joint angle) were collected during a normal working day in all workstations of both lines after two hours of assembly work. Video recordings were carried out simultaneously with direct measurements of operators' upper-limb mechanical exposure. Implemented task rotation schemes in the production area made it easier data collection procedures. The seven selected participants had skills to performance all tasks of the workstations of both assembly lines. In each workstation were assessed two participants, after completing at least four work cycles. This procedure was performed in order to not to interfere with the line efficiency. The movements of the participants were recorded by a full body inertial motion capture called Xsens MVN BIOMECH system (Xsens Technologies BV, Enschede, Netherlands). This system can estimate body segment orientation and position changes by integration of gyroscope and accelerometer signals which are continuously updated using a biomechanical human body model. The equipment has 17 MTx sensors with two Xbus Masters. The MTx sensors are an inertial and magnetic measurement unit that contains 3D gyroscopes, 3D accelerometers and 3D magnetometers (Roetenberg, Luinge, & Slycke, 2009). Before each trial, the inertial acquisition system was calibrated with the anthropometric data of the subjects (Xsens Technologies B.V., 2011). Data capture was done through a graphical interface (Moven Studio V3.1; Xsens Technologies BV, Ensched, Netherlands). A kinematic coupling algorithm (KiC^{TM}) was implemented to reduce magnetic disturbances. Positions of anatomical landmarks were placed according to the orientations of the sensors in combination with the biomechanical model. Figure 20 shows the location set for the sensors modules. Inertial data were collected at a sampling rate of 100 Hz. Due to the dominance in the performance of assembly tasks, data were analyzed from the angular position of the right arm.

7.2.4. Statistical Analysis

Descriptive statistics of joint angles over time were calculated to the subjects at each workstation. The waveform similarity over work cycles was calculated to evaluate intertrial repeatability using the maximum cross-correlation. Cross-correlation was determined between subjects in each workstation and between subjects in the workstations of the M1 vs A1, A3 and M3 vs M4 vs A4 of the two assembly lines in study (Manual vs. Semi-automated). Maximum cross-correlation values quantified the waveform similarity with values between 0.1 and 0.3 as weak, 0.3 and 0.5 as moderate and 0.5 and 1 as strong (DeGroot & Schervish, 2011). All statistical analysis were completed using *R* version 3.1.1. A *p*-value less than 0.05 was regarded as statistically significant.

Figure 20. Positioning of inertial sensor modules.

7.3. Results

The upper-limb mechanical exposure was assessed by direct measurements of joint angles of the right arm (dominant hand) in real-occupational setting (Figure 21). Table 13 shows means and percentiles of joint angles at each workstation. The manual line exhibited a wider range (5-95th percentiles) of motion for the shoulder, in particular, for the abduction/adduction and internal/external rotation at workstation M3. In the workstation M2 it was also found a large variation for the joint flexion/extension angle. Ulnar wrist deviation was reached values above 20° at all workstations. In the semi-automated line, the elbow flexion angle was higher than 60º (118.53º) in the workstation A2. Additionally, the wrist ulnar/radial deviation angle ranged between -11.55° and 31.52°. As at the manual line, ulnar wrist deviation reached amplitudes higher than 20°.

Wrist flexion/extension angle showed a higher variation than the manual line. In manual line, the waveform similarity between subjects in each workstation was greater for shoulder joint than for the other regions. Wrist joint showed the smallest cross correlation coefficients values. Similar results were found to the semi-automated line. The comparative analysis between workstations of two lines (Table 14) indicates that M4 and A4 had very good repeatability among workers for shoulder abduction/adduction movement. All coefficients were statistically significant ($p<0.001$).

Figure 21. Workplace measurements.

Table 13. Mean (SD) and percentiles of joint angles. Flexion, abduction, ulnar wrist deviation, pronation and internal rotation are positive (+); extension, adduction, radial wrist deviation, supination and external rotation are negative (-) (n=7).

Joint	Motion	***Manual Line***						***Semi-automated Line***			
		M1	M2	M3	M4	M5	M6	A1	A2	A3	A4
Mean angle (°) Percentiles (°)											
Shoulder	***AB/AD***	*20.79 (±0.19)*	*34.51(±0.35)*	*12.89 (±0.68)*	*18.65 (±7.35)*	*9.91 (±0.81)*	*17.64 (±0.72)*	*13.24 (±1.96)*	*33.30 (±0.35)*	*13.87 (±6.67)*	*6.70 (±1.49)*
	5th	10.73	22.01	**-5.33**	15.19	**-7.74**	6.37	9.00	9.07	-0.54	-5.67
	50th	21.48	35.64	**9.67**	17.96	**7.66**	18.60	11.68	30.68	10.34	5.84
	95th	29.91	41.61	**29.92**	23.,69	**31.86**	26.82	24.56	60.36	32.37	23.04
	IN/EX	*19.78 (±1.84)*	*15.07(±1,50)*	*17.60 (±0.28)*	*-3.19 (±2.97)*	*24.93 (±2.72)*	*11.93 (±0.79)*	*20.62 (±5.48)*	*10.34 (±1.21)*	*19.04 (±4.33)*	*41.44 (±3.04)*
	5th	30.86	-36.60	**-10.25**	-12.87	0.29	**-3.06**	0.11	-24.29	-9.75	16.24
	50th	40.92	-16.19	**18.89**	-2.94	28.88	**9.45**	22.18	13.65	22.27	44.10
	95th	39.78	11.66	**43.94**	7.26	37.99	**34.94**	30.21	33.34	36.76	59.91
	F/E	*10.48 (±0.53)*	*18.44 (±1.40)*	*31.15 (±0.39)*	*11.12 (±1.91)*	*32.78 (±3.46)*	*24.80 (±1.08)*	*12.82 (±13.24)*	*22.61 (±2.90)*	*34.77 (±4.87)*	*30.91 (±0.81)*
	5h	39.05	**-6.17**	13.06	2.87	5.17	6.78	5.31	-19.40	3.63	16.01
	50th	86.39	**14.22**	30.73	10.92	38.28	23.96	12.78	23.78	34.98	30.08
	95th	34.06	**47.66**	45.38	19.83	47.30	42.12	19.23	53.83	56.02	45.19
Elbow	***F/E***	*80.55 (±0.08)*	*50,06 (±1,51)*	*37.64 (±0.41)*	*65.47 (±5.47)*	*48.97 (±1.50)*	*60.90 (±4.47)*	*66.44 (±11.13)*	*77.11 (±26.15)*	*38.13 (±4.84)*	*55.03 (±7.97)*
	5th	40.25	25.95	24.12	50.10	27.86	**20.08**	53.25	**33.80**	5.33	37.09
	50th	86.34	52.04	36.81	65.99	47.11	**51.37**	67.68	**75.31**	37.00	55.94
	95th	95.13	69.95	52.83	75.94	79.73	**111.76**	74.32	**118.53**	65.81	71.96
Forearm	***P/S***	-2.77 (±1.77)	13.20 (±1.58)	7.84 (±0.34)	-1.91 (±4.42)	5.02 (±8.28)	-10.25 (±5.02)	-28.74 (±0.28)	19.39 (±26.77)	18.84 (±7.11)	6.35 (±14.97)
	5th	-14.19	4.85	**-17.78**	-20.08	-10,64	-25.09	-41.75	-8.58	-4.96	-18.31
	50th	-7.55	12.89	**10.09**	-2.27	0,82	-10.07	-33.99	22.20	19.33	10.19
	95tn	26.52	22.71	**32.27**	14.21	38,19	4.07	8.09	36.75	41.87	20.72
Wrist	***R/U***	*13.21 (±1.46)*	*14.39 (±0.99)*	*11.19 (±3.68)*	*20.71 (±7.63)*	*12.43 (±0.79)*	*15.78 (±0.42)*	*12.46 (±2.34)*	*11.13 (±7.02)*	*25.03 (±4.84)*	*14.56 (±22.13)*
	5th	0.33	-14.76	-3.83	5.89	-6.35	-5.13	4.95	**-11.55**	3.18	-9.58
	50th	13.07	19.11	11.72	22.85	12.76	15.03	10.66	**11.74**	24.52	16.14
	95th	27.83	28.81	23.26	34.45	31.80	43.46	31.14	**31.62**	52.40	33.06
	F/E	*-27.66 (±1.68)*	*-6.96 (±3.73)*	*-41.53 (±0.44)*	*-10.29 (±12.68)*	*15.48 (±10.82)*	*-22.45 (±9.22)*	*-52.19 (±15.98)*	*-28.74 (±2.94)*	*-25.53 (±4.85)*	*-31.09 (±10.46)*
	5th	-41.02	-19.39	-58.62	-29.46	0.52	-40.83	-63.50	-46.56	**-60.02**	-47.04
	50th	-27.80	-8.60	-43.98	-7.57	14.18	-23.85	-54.12	-29.84	**-25.22**	-32.59
	95th	-13.08	10.67	-18.75	5.17	35.39	0.41	-31.77	-9.03	**11.38**	-9.23

Motion abbreviation: flexion/extension (F/E), adduction/abduction (AB/AD), internal/external rotation (IN/EX), supination/pronation (P/S), and radial/ulnar deviation (R/U).

Table 14. Coefficients of cross correlation of the upper-limb joints (n=7).

		Shoulder			Elbow	Forearm	Wrist	
Manual Line								
Workstation	**Subjects**	(x) Abduction(+)/ Adduction (-)	(y) Internal (+)/ External (-) Rotation	(z) Flexion (+)/ Extension (-)	(z) Flexion (+)/ Extension (-)	(y) Pronation (+)/ Supination (-)	(x) Ulnar deviation (+)/ Radial deviation (-)	(z) Flexion (+)/ Extension (-)
		r	r	r	R	r	R	r
M1	1 vs. 2	**0.5**	**0.5**	**0.7**	**0.7**	**0.7**	**0.5**	0.4
M2	1 vs. 2	**0.7**	**0.5**	**0.6**	**0.7**	**0.6**	**0.8**	**0.6**
M3	1 vs. 2	**0.7**	**0.6**	**0.6**	**0.6**	**0.5**	0.3	**0.5**
M4	1 vs. 2	**0.6**	**0.6**	0.3	**0.5**	0.2	0.3	0.4
M5	1 vs. 2	**0.7**	**0.7**	**0.7**	0.4	**0.6**	0.4	**0.5**
M6	1 vs. 2	**0.6**	**0.7**	**0.7**	**0.6**	**0.6**	**0.5**	**0.6**
Semi-automated Line								
A1	1 vs. 2	**0.7**	**0.6**	**0.6**	**0.5**	**0.5**	0.4	**0.5**
A2	1 vs. 2	**0.5**	0.4	0.4	0.4	0.4	0.3	0.3
A3	1 vs. 2	**0.7**	**0.6**	**0.5**	**0.5**	0.4	**0.6**	0.4
A4	1 vs. 2	0.3	**0.5**	**0.5**	**0.6**	0.3	0.3	**0.5**
Manual Line vs Semi-automated Line								
M1 vs. A1	1 vs. 1	0.3	0.4	0.4	0.3	0.4	**0.5**	0.3
	1 vs. 2	**0.5**	0.4	0.4	**0.5**	0.3	0.3	0.3
	2 vs. 1	0.4	0.2	0.3	0.4	0.4	**0.7**	0.3
	2 vs. 2	**0.5**	0.3	0.4	**0.6**	0.4	**0.5**	**0.5**
M3 vs. A3	1 vs. 1	**0.7**	0.4	**0.5**	0.3	0.4	0.3	0.1
	1 vs. 2	**0.8**	**0.5**	0.4	0.3	0.4	0.4	0.3
	2 vs. 1	**0.6**	**0.5**	0.4	**0.5**	0.3	0.3	**0.5**
	2 vs. 2	**0.6**	0.4	0.4	0.3	0.4	0.3	0.3
	1 vs. 1	0.2	0.4	0.4	0.2	0.3	0.4	0.4
M4 vs. A4	1 vs. 1	**0.5**	**0.5**	0.3	0.3	0.2	**0.5**	0.3
	1 vs. 2	**0.6**	0.3	**0.5**	0.3	0.2	0.4	0.4
	2 vs. 1	**0.5**	0.2	0.4	0.4	0.3	0.4	0.3
	2 vs. 2	**0.7**	0.4	**0.5**	0.3	0.4	0.3	0.1
	1 vs. 1	**0.8**	**0.5**	0.4	0.3	0.4	0.4	0.3

*All cross-correlations showed P-value less than 0.001.

7.4. Discussion

The development of assembly lines with high levels of automation aims at reducing the physical workload, minimizing WMSDs. The results of inertial motion capture system for joint angles showed that the manual line had the greatest variation of the joint amplitude, in particular, to the shoulder, elbow and forearm. However, in both lines elbow and wrist joint angles reached values above the threshold recommended by ISO 11228-3 2007 (ISO, 2007) (awkward posture: >60° for elbow and >20° for wrist). Palmerud et al. (2012) found that wrist deviation and wrist flexion (on the non-dominant side) were significantly lower in a conventional serial flow assembly line, where workers perform a few number of assembly actions, than in a parallel assembly line with a long-cycle flow. Other study carried out by Womack, Armstrong & Liker (2009) also showed that no significant differences were found in wrist and shoulder postures between a lean automobile-manufacturing (5–8 production workers per team) and a traditional automobile- manufacturing plant (18–20 production workers per team).

In fact, automation with human interaction is essential to lean manufacturing (Genaidy & Karwowski, 2003) and there is no consensus about the effects of Lean Production Systems (LPS) on the musculoskeletal health. Some authors referred positive impacts of LPS (Hunter, 2008; Johansson & Abrahamsson, 2009), while others reported negative effects. The results of Balogh, Ohlsson, Hansson, Engström & Skerfving (2006) study showed that increased mechanization of assembly lines implies absence of posture and movements' variation and, in the case of the semi-automated line, more constrained postures were found. The present results may have been influenced by other factors such as age, gender, body mass index (BMI), arm and forearm circumferences and physical activity (Chapleau et al., 2013).

The application of an inertial motion capture system is able to estimate angular kinematics for the upper limbs in assembly-line workers. In the records performed, the cross correlation obtained for the similarity of movements was from moderate to strong. However, this similarity is more evident when comparing workers from the manual line. These results can be explained by the influence of several poke yokes systems (using electromagnetic radiation) installed in the semi-automated line. Additionally, the semi-automated line was near to a wireless access point and plastic injection machines. According to Brodie, Walmsley & Page (2008) metal physical barriers increased measurement errors in the inertial systems. In general, the weaker cross correlation values were found for the wrist joint which can be explained by the proximity of this body region with the equipment and machinery.

Hence, these results have to be interpreted with caution because inertial motion capture systems depend on kinematic characteristics of a task such as motion speed (Kim & Nussbaum, 2013). Comparing the tasks of the different lines (manual line vs semi-automated line), the differences between subjects are more obvious. Although they have comparable tasks, system accuracy may have been affected by the movement characteristics involved in the tasks. The present field study has several limitations. Data collection was performed in a short work time periods (ten minutes) to avoid interference to with production. Additionally, when the worker presses the control buttons in the assembly line, some disturbances are observed in the data capture system (Moven Studio V3.1; Xsens Technologies BV, Ensched, Netherlands). It was found that over the time, the inertial system was influenced by the typical magnetic interferences of an industrial environmental. Another limitation was associated with the small sample size.

7.5. Conclusions

The results of this study led to the conclusion that the mechanization from the manual to the semi-automated line implied the lowest range of motion. However, both lines showed constrained elbow and wrist postures. The results also demonstrated that the applications of a full-body inertial measurement in assembly work under realistic conditions have some restrictions caused by the influence of electromagnetic interferences.

7.6. References

Balogh, I., Ohlsson, K., Hansson, G. Å., Engström, T., & Skerfving, S. (2006). Increasing the degree of automation in a production system: Consequences for the physical workload. *International Journal of Industrial Ergonomics*, *36*(4), 353–365.

Battini, D., Faccio, M., Ferrari, E., Persona, A., & Sgarbossa, F. (2007). Design configuration for a mixed-model assembly system in case of low product demand. *International Journal of Advanced Manufacturing Technology*, *34*(1-2), 188–200.

Bin Wong, S., & Richardson, S. (2010). Assessment of working conditions in two different semiconductor manufacturing lines: Effective ergonomics interventions. *Human Factors and Ergonomics in Manufacturing & Service Industries*, 20*(5)*, 391–407.

Boysen, N., Fliedner, M., & Scholl, A. (2007). A classification of assembly line balancing problems. *European Journal of Operational Research*, *183*(2), 674–693.

Brodie, M. A., Walmsley, A., & Page, W. (2008). The static accuracy and calibration of inertial measurement units for 3D orientation. *Computer Methods in Biomechanics and Biomedical Engineering*, *11*(6), 641–648.

Chapleau, J., Canet, F., Petit, Y., Sandman, E., Laflamme, G. Y., & Rouleau, D. M. (2013). Demographic and anthropometric factors affecting elbow range of motion in healthy adults. *Journal of Shoulder and Elbow Surgery*, *22*(1), 88–93.

Coury, H. J. C. G., Léo, J. A., & Kumar, S. (2000). Effects of progressive levels of industrial automation on force and repetitive movements of the wrist. *International Journal of Industrial Ergonomics*, *25*(6), 587–595.

Cutti, A. G., Giovanardi, A., Rocchi, L., Davalli, A., & Sacchetti, R. (2008). Ambulatory measurement of shoulder and elbow kinematics through inertial and magnetic sensors. *Medical and Biological Engineering and Computing*, *46*(2), 169–178.

DeGroot, M. H., & Schervish, M. J. (2011). Probability and Statistics (4th ed., p. 912). Pearson.

Eurofound. (2012). Fifth European Working Conditions Survey. Luxembourg: Publications Office of the European Union.

Garg, A., & Kapellusch, J. M. (2009). Applications of biomechanics for prevention of work-related musculoskeletal disorders. *Ergonomics*, *52*(1), 36–59.

Genaidy, A. M., & Karwowski, W. (2003). Human performance in lean production environment: Critical assessment and research framework. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *13*(4), 317–330.

Hunter, S. L. (2008). The Toyota production system applied to the upholstery furniture manufacturing industry. *Materials and Manufacturing Processes*, *23*(7), 629-634.

ISO. (2007). ISO 11228-3 Ergonomics — Manual handling — Part 3: Handling of low loads at high frequency (pp. 76). Geneva: International Standard Organization.

Johansson, J., & Abrahamsson, L. (2009). The good work - A Swedish trade union vision in the shadow of lean production. *Applied Ergonomics*, *40*(4), 775–780.

Kim, S., & Nussbaum, M. A. (2013). Performance evaluation of a wearable inertial motion capture system for capturing physical exposures during manual material handling tasks. *Ergonomics*, *56*(2), 314–26.

Marras, W. S., Cutlip, R. G., Burt, S. E., & Waters, T. R. (2009). National occupational research agenda (NORA) future directions in occupational musculoskeletal disorder health research. *Applied Ergonomics*, *40*(1), 15-22.

Neumann, W. P., Winkel, J., Medbo, L., Magneberg, R., & Mathiassen, S. E. (2006). Production system design elements influencing productivity and ergonomics: A case study of parallel and serial flow strategies. *International Journal of Operations & Production Management*, *26*(8), 904 - 923.

Neumann, W. P., Kihlberg, S., Medbo, P., Mathiassen, S. E., & Winkel, J. (2002). A case study evaluating the ergonomic and productivity impacts of partial automation strategies in the electronics industry. *International Journal of Production Research*, *40*(16), 4059-4075.

Palmerud, G., Forsman, M., Neumann, W. P., & Winkel, J. (2012). Mechanical exposure implications of rationalization: A comparison of two flow strategies in a Swedish manufacturing plant. *Applied Ergonomics*, *43*(6), 1110–1121.

Qin, J., Lin, J. H., Faber, G. S., Buchholz, B., & Xu, X. (2014). Upper extremity kinematic and kinetic adaptations during a fatiguing repetitive task. *Journal of Electromyography and Kinesiology*, *24*(3), 404–411.

Roetenberg, D., Luinge, H., & Slycke, P. (2009). Xsens MVN: full 6DOF human motion tracking using miniature inertial sensors. Xsens Motion Technologies BV,…, 1–7. Retrieved from http://www.xsens.com/images/stories/PDF/MVN_white_paper.pdf

Toksari, M. D., Işleyen, S. K., Güner, E., & Baykoç, Ö. F. (2008). Simple and U-type assembly line balancing problems with a learning effect. *Applied Mathematical Modelling*, *32*(12), 2954–2961.

Wei, N. C., & Chao, I. M. (2011). A solution procedure for type E simple assembly line balancing problem. *Computers & Industrial Engineering*, *61*(3), 824–830.

Wells, R., Mathiassen, S. E., Medbo, L., & Winkel, J. (2007). Time-A key issue for musculoskeletal health and manufacturing. *Applied Ergonomics*, *38*(6), 733–744.

Westgaard, R. H., & Winkel, J. (2011). Occupational musculoskeletal and mental health: Significance of rationalization and opportunities to create sustainable production systems - A systematic review. *Applied Ergonomics*, *42*(2), 261-296.

Womack, S. K., Armstrong, T. J., & Liker, J. K. (2009). Lean job design and musculoskeletal disorder risk: A two plant comparison. *Human Factors and Ergonomics In Manufacturing*, *19*(4), 279–293.

Xsens Technologies B.V. (2011). MVN user Manual.

Yeh, D. H., & Kao, H. H. (2009). A new bidirectional heuristic for the assembly line balancing problem. *Computers and Industrial Engineering*, *57*(4), 1155–1160.

CHAPTER 8: General Discussion, Main Findings and Future Research

8.1. General discussion and conclusions

EMG variables are widely used to investigate the influence of temporal organization of work and job rotation during repetitive tasks. A literature review was conducted (chapter III) in order to understand the influence of job rotation and work-rest schemes, as well as, work pace, cycle time and duty cycle, on upper limb muscle activity and fatigue and other physiological responses during low load work. Few studies were performed in real work conditions and the introduction of rest breaks seems to be a more effectively intervention to reduce muscle fatigue and discomfort. However, job rotation did not appear as an effective measure in all studies.

In order to measure perceived fatigue at work is important to use valid instruments that incorporate all aspects that characterize this multidimensional phenomenon. SOFI contributes to understand the concept of fatigue by investigating the subjective qualities of fatigue in different working populations. However, there was no Portuguese version available of SOFI. Therefore, a cross sectional study was conducted in chapter IV, to analyze the psychometric properties of the Portuguese version of the SOFI on a sample of assembly workers. Two different models were tested: a model with 20 variables evenly distributed on five latent variables and a nested model. The results revealed that items in Portuguese language were well discriminated in five dimensions. All goodness of fit indices showed an overall good model adjustment. Therefore, this version is an adequate tool to apply in other working populations.

In chapter V, EMG variables were recorded during three test contractions over the course of 8 hours working day. In addition, a uni-dimensional scale (CR-10 Borg Scale) and multidimensional scale (Portuguese version of SOFI) were applied to evaluated perceived exertion and fatigue, respectively. Changes of MF and RMS during contraction period (analyzed by linear regression) demonstrated that extensor carpi radialis muscle (ECR) and flexor carpi radialis muscle (FCR) were fatigued. However, there was no significant influence of working time in these variables. Forearm muscles consist of several muscles in close proximity and with varying degrees of common function, being therefore possible that in real work conditions, workers may adopt different postures over the course of work in order to distribute the load between them, reducing the effects of fatigue. On the other hand, rotation of motor unit activity at low level contractions can occur in the absence of postural changes (during predefined test contractions), which can also be a helpful mechanism to prevent muscle fatigue (Movahed, Ohashi, Kurustien, Izumi, & Kumashiro, 2011). Moreover, some limitations of surface EMG to detect fatigue at low-level isometric efforts have been reported (Blangsted, Sjøgaard, Madeleine, Olsen, & Søgaard, 2005; Yassierli & Nussbaum, 2008). According to Farina, Holobar, Merletti, & Enoka (2010), despite advances in surface EMG processing, the identification of the discharge times of individual motor units during dynamic contractions and to low forces is still limited. High-density EMG surface has been reported as an alternative non-invasive technique to study the behavior of individual motor units (Holobar, Farina, Gazzoni, Merletti, & Zazula, 2009; Merletti, Botter, Troiano, Merlo, & Minetto, 2009; Merletti, Holobar, & Farina, 2008). Despite the potentialities of this system for quantifying fatigue during working tasks, improvements are still needed regarding signal acquisition and interpretation, particularly in field conditions (Gazzoni, 2010). In addition, the application of multi-channel detection systems over the skin surface require more time consuming than the use of classic bipolar electrode systems (Holobar et al., 2009); therefore, this last system seemed to be more practicable in the present field study. All dimensions of rating SOFI and Borg CR-10 scores increased with time, demonstrating therefore more sensitive to fatigue. However, the workers perception throughout the working day can be influenced by conflicts between colleagues or/and decisions related to production.

In order to determine EMG manifestations of fatigue for a more extended exposure to repetitive tasks in rotation and non-rotation conditions, a study presented in the chapter IV was performed. In this study, also the proprioceptive acuity was assessed. Overall, results demonstrated some benefits in the implementation of job rotation. However, considering that the manual assembly tasks often required the same muscle groups and joints, an effective alternative intervention to increase variation in biomechanical exposure may be related to intrinsic variability of the motor system (motor variability), i.e. variation in postures, movements and muscle activity during the performance of tasks. According to Srinivasan & Mathiassen (2012) job rotation is an “extrinsic” method with inconclusive practical results in literature, so it was proposed that interventions with the objective of changing the way the operator performs the task (implementation of “intrinsic” sources of exposure variation) can be a viable alternative.

In chapter V, a pilot study that evaluates the performance of a full-body inertial measurement system in real work conditions is presented. The results reinforce the need to improve the performance of an inertial measurement unit (IMU) system under dynamic common conditions in working environments (Kim & Nussbaum, 2013).

8.2. Future research

Several investigation questions were brought to light in this thesis, requiring further supporting evidences and scientific clarification. The following matters should be addressed in future research related to repetitive work:

- To compare muscle activity of forearm muscles among long-term experience and less experienced workers;
- To compare muscle activity of forearm muscles among workers with long recovery periods (after holiday period) and workers with long periods of work;
- To determine the relationships between motor variability in repetitive tasks and outcomes as fatigue and performance.
- To analyze the development of muscle fatigue in older and in an obese worker population;
- To develop the cultural adaptation of other scales to measure work-related fatigue and recovery between work shifts as Occupational Fatigue Exhaustion/Recovery Scale (OFER)
- To assess localized muscle fatigue using new technologies such as Body Interface System based on Wearable Integrated Monitorization developed by INESC Tech.

8.3. References

Blangsted, A. K., Sjøgaard, G., Madeleine, P., Olsen, H. B., & Søgaard, K. (2005). Voluntary low-force contraction elicits prolonged low-frequency fatigue and changes in surface electromyography and mechanomyography. *Journal of Electromyography and Kinesiology*, *15*(2), 138–148.

Farina, D., Holobar, A., Merletti, R., & Enoka, R. M. (2010). Decoding the neural drive to muscles from the surface electromyogram. *Clinical Neurophysiology*, *121*(10), 1616-1623.

Gazzoni, M. (2010). Multichannel surface electromyography in ergonomics: Potentialities and limits. *Human Factors and Ergonomics In Manufacturing*, *20*(4), 255–271.

Holobar, A., Farina, D., Gazzoni, M., Merletti, R., & Zazula, D. (2009). Estimating motor unit discharge patterns from high-density surface electromyogram. *Clinical Neurophysiology*, *120*(3), 551–562.

Kim, S., & Nussbaum, M. A. (2013). Performance evaluation of a wearable inertial motion capture system for capturing physical exposures during manual material handling tasks. *Ergonomics*, *56*(2), 314–26.

Merletti, R., Botter, A., Troiano, A., Merlo, E., & Minetto, M. A. (2009). Technology and instrumentation for detection and conditioning of the surface electromyographic signal: State of the art. *Clinical Biomechanics*, *24*(2), 122-134.

Merletti, R., Holobar, A., & Farina, D. (2008). Analysis of motor units with high-density surface electromyography. *Journal of Electromyography and Kinesiology*, *18*(6), 879–890.

Movahed, M., Ohashi, J. Y., Kurustien, N., Izumi, H., & Kumashiro, M. (2011). Fatigue sensation, electromyographical and hemodynamic changes of low back muscles during repeated static contraction. *European Journal of Applied Physiology*, *111*(3), 459–467.

Srinivasan, D., & Mathiassen, S. E. (2012). Motor variability in occupational health and performance. *Clinical Biomechanics*, *27*(10), 979-993.

Yassierli, & Nussbaum, M. A. (2008). Utility of traditional and alternative EMG-based measures of fatigue during low-moderate level isometric efforts. *Journal of Electromyography and Kinesiology*, *18*(1), 44–53.

APPENDICES

Appendix A: Demographic characteristics and health status questionnaire

Fadiga Muscular e Desconforto no Trabalho

Questionário ao Trabalhador

Estado de Saúde Geral e Caracterização da Atividade Profissional

CÓDIGO:

DATA DE PREENCHIMENTO:

IDENTIFICAÇÃO DO TRABALHADOR

Nº mecanográfico:	
Nome:	
Data de Nascimento:	
Idade:	
Nacionalidade:	
Naturalidade:	
Estado Civil:	
Habilitações literárias:	
Sector/Linha/Posto de Trabalho:	
Horário de Trabalho:	
Nº de horas de trabalho diário:	
Nível de Polivalência*:	

*Esta informação é específica da empresa.

Fadiga Muscular e Desconforto no Trabalho

Questionário ao Trabalhador

Estado de Saúde Geral e Caracterização da Atividade Profissional

DADOS PESSOAIS

1. Peso:	2. Altura:
3. Membro dominante:	Dextro ☐ Esquerdino ☐ Ambidextro ☐
4. Sofre de alguma doença?	Sim ☐ Não ☐
4.1. Se sim, qual?	
5. Toma algum tipo de medicação?	Sim ☐ Não ☐
5.1. Se sim, qual?	
6. Faz algum tipo de tratamento ou reabilitação?	Sim ☐ Não ☐
6.1. Se sim, qual?	
7. Possui hábitos tabágicos?	Sim ☐ Não ☐
7.1. Quantidade:	
8. Consume álcool?	Sim ☐ Não ☐
8.1. Quantidade:	
9. Pratica exercicio fisico?	Sim ☐ Não ☐

Fadiga Muscular e Desconforto no Trabalho

Questionário ao Trabalhador

Estado de Saúde Geral e Caracterização da Atividade Profissional

9.1. Se sim, qual?	
9.2. Quantas horas por semana?	

Fadiga Muscular e Desconforto no Trabalho

Questionário ao Trabalhador

Estado de Saúde Geral e Caracterização da Atividade Profissional

DADOS RELATIVOS À ATIVIDADE PROFISSIONAL

10. Há quantos anos trabalha nesta empresa?	
10.1. Há quanto tempo se encontra no posto de trabalho atual?	
10.2. Quais os postos de trabalho anteriores (mais importantes)?	
11. Quantas pausas tem ao longo do turno de trabalho (nº de pausas e horário da pausa)?	
11.1. Qual a duração das pausas?	
12. Profissões anteriores (designação e tempo de trabalho):	
13. Tem outra atividade profissional?	Sim ☐ Não ☐
13.1. Qual?	
14. Já teve algum acidente de trabalho?	Sim ☐ Não ☐
14.1. Se sim, que tipo de lesão teve?	

Fadiga Muscular e Desconforto no Trabalho

Questionário ao Trabalhador

Estado de Saúde Geral e Caracterização da Atividade Profissional

15. Sofre de alguma doença profissional?	Sim ☐ Não ☐
15.1. Se sim, qual?	
16. Já teve alguma lesão músculo-esquelética?	Sim ☐ Não ☐
16.1. Se sim, em que região do corpo?	
16.2. Que tipo de lesão?	
17. Sente desconforto muscular durante ou após a realização a sua atividade profissional?	Sim, sempre ☐ Sim, às vezes ☐ Não, nunca ☐
18. Sente fadiga generalizada após a realização da sua atividade profissional?	Sim, sempre ☐ Sim, às vezes ☐ Não, nunca ☐
19. Já teve formação/informação relativa a posturas corretas no local de trabalho?	Sim ☐ Não ☐

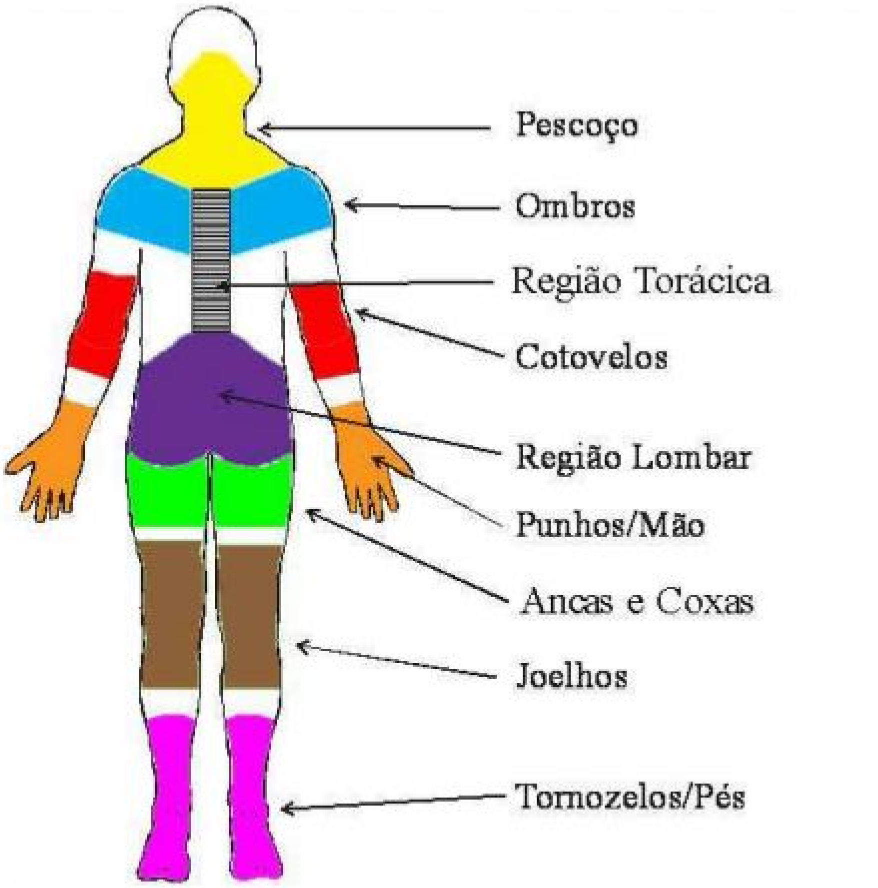
Obs.:____

Appendix B: Portuguese version of the standardized Nordic musculoskeletal questionnaire

Questionário Nórdico Músculo-esquelético

Instruções para o preenchimento

- Por favor, responda a cada questão assinalando um "X" na caixa apropriada: ☒
- Marque apenas um "X" por cada questão.
- Não deixe nenhuma questão em branco, mesmo se não tiver nenhum problema em qualquer parte do corpo.
- Para responder, considere as regiões do corpo conforme ilustra a figura abaixo.



Versão portuguesa: Cristina Carvalho Mesquita
Contacto para autorização de utilização: ccm@estsp.ipp.pt

Questionário Nórdico Músculo-esquelético

Código:

Idade_____Data de nascimento____/___/___Sexo_________Data de hoje____/____/_____

Posto de trabalho_________________________________Estado civil__________________

Nome____

Considerando os **últimos 12 meses**, teve algum **problema (tal como dor, desconforto ou dormência)** nas seguintes regiões:	**Responda, apenas, se tiver algum problema** Durante os **últimos 12 meses** teve que evitar as suas actividades normais (trabalho, serviço doméstico ou passatempos) por causa de **problemas** nas seguintes regiões:	Teve algum problema nos **últimos 7 dias**, nas seguintes regiões:	
1. Pescoço? Não Sim 1 2	2. Pescoço? Não Sim 1 2	3. Pescoço? Não Sim 1 2	4. Sem Dor 0 1 2 3 4 5 6 7 8 9 10 Dor Máxima
5. Ombros? Não Sim 1 2 , no ombro direito 3 , no ombro esquerdo 4 , em ambos	6. Ombros? Não Sim 1 2 , no ombro direito 3 , no ombro esquerdo 4 , em ambos	7. Ombros? Não Sim 1 2 , no ombro direito 3 , no ombro esquerdo 4 , em ambos	8. Sem Dor 0 1 2 3 4 5 6 7 8 9 10 Dor Máxima
9. Cotovelo? Não Sim 1 2 , no cotovelo direito 3 , no cotovelo esquerdo 4 , em ambos	10. Cotovelo? Não Sim 1 2 , no cotovelo direito 3 , no cotovelo esquerdo 4 , em ambos	11. Cotovelo? Não Sim 1 2 , no cotovelo direito 3 , no cotovelo esquerdo 4 , em ambos	12. Sem Dor 0 1 2 3 4 5 6 7 8 9 10 Dor Máxima
13. Punho/Mãos? Não Sim 1 2 , no punho/mãos direitos 3 , no punho/mãos esquerdos 4 , em ambos	14. Punho/Mãos? Não Sim 1 2 , no punho/mãos direitos 3 , no punho/mãos esquerdos 4 , em ambos	15. Punho/Mãos? Não Sim 1 2 , no punho/mãos direitos 3 , no punho/mãos esquerdos 4 , em ambos	16. Sem Dor 0 1 2 3 4 5 6 7 8 9 10 Dor Máxima
17. Região Torácica? Não Sim 1 2	18. Região Torácica? Não Sim 1 2	19. Região Torácica? Não Sim 1 2	20. Sem Dor 0 1 2 3 4 5 6 7 8 9 10 Dor Máxima
21. Região Lombar? Não Sim 1 2	22. Região Lombar? Não Sim 1 2	23. Região Lombar? Não Sim 1 2	24. Sem Dor 0 1 2 3 4 5 6 7 8 9 10 Dor Máxima
25. Ancas/Coxas? Não Sim 1 2	26. Ancas/Coxas? Não Sim 1 2	27. Ancas/Coxas? Não Sim 1 2	28. Sem Dor 0 1 2 3 4 5 6 7 8 9 10 Dor Máxima
29. Joelhos? Não Sim 1 2	30. Joelhos? Não Sim 1 2	31. Joelhos? Não Sim 1 2	32. Sem Dor 0 1 2 3 4 5 6 7 8 9 10 Dor Máxima
33. Tornozelo/Pés? Não Sim 1 2	34. Tornozelo/Pés? Não Sim 1 2	35. Tornozelo/Pés? Não Sim 1 2	36. Sem Dor 0 1 2 3 4 5 6 7 8 9 10 Dor Máxima

Versão portuguesa: Cristina Carvalho Mesquita
Contacto para autorização de utilização: ccm@estsp.ipp.pt

Appendix C: Portuguese version of Swedish Occupational Fatigue Inventory (SOFI)

Pense no que sentiu na altura em que esteve mais cansado(a). Em que medida as expressões abaixo descrevem como se sentiu? Para cada expressão, responda de forma espontânea, e marque **com uma cruz (X)** o número que corresponde a **como se sente agora.** Os números variam entre 0 (nada) e 6 (muitíssimo).

	Nada						**Muitíssimo**
Com palpitações	0	1	2	3	4	5	6
Falta de envolvimento	0	1	2	3	4	5	6
Desgastado(a)	0	1	2	3	4	5	6
Com tensão muscular	0	1	2	3	4	5	6
A adormecer	0	1	2	3	4	5	6
Com dormência	0	1	2	3	4	5	6
A suar	0	1	2	3	4	5	6
Extenuado(a)	0	1	2	3	4	5	6
Com preguiça	0	1	2	3	4	5	6
Passivo(a)	0	1	2	3	4	5	6
Com articulações rígidas	0	1	2	3	4	5	6
Indiferente	0	1	2	3	4	5	6
Com falta de ar	0	1	2	3	4	5	6
A bocejar	0	1	2	3	4	5	6
Exausto(a)	0	1	2	3	4	5	6
Sonolento(a)	0	1	2	3	4	5	6
Sobrecarregado(a)	0	1	2	3	4	5	6
Com dores	0	1	2	3	4	5	6
Ofegante	0	1	2	3	4	5	6
Desinteressado(a)	0	1	2	3	4	5	6

Appendix D: Borg's CR-10 Scale

Escala CR10 de Borg

A presente escala destina-se a avaliar a **intensidade do esforço** durante a realização da sua atividade de trabalho.

Queremos saber a sua perceção sobre o **esforço efetuado** ou **força aplicada com a mão/dedos**, de acordo com as expressões referidas.

Marque (com um X) o algarismo que corresponde a **como se sente agora**.

Não existem respostas certas ou erradas, pelo que a sua **opinião sincera e espontânea** é muito importante.

Escala CR10 de Borg

Score	Expressão verbal	Assinale com um (X)
0	Não existe esforço	
0.3		
0.5	Esforço extremamente ligeiro (quase impercetível)	
0.7		
1	Esforço muito ligeiro	
1.5		
2	Esforço ligeiro	
2.5		
3	Esforço moderado	
4		
5	Esforço intenso	
6		
7	Esforço muito intenso	
8		
9		
10	Esforço extremamente intenso (máximo)	
11		
●	Esforço “extremo”	

Appendix E: Search strategy in databases

Search strategy used in Pubmed:

*muscle fatigue[Title/Abstract] AND upper limbs[Title/Abstract] AND (Journal Article[ptyp] AND English[lang])

*muscle fatigue[Title/Abstract] AND forearm muscles[Title/Abstract] AND (Journal Article[ptyp] AND English[lang])

*muscle fatigue[Title/Abstract] AND workload[Title/Abstract] AND (Journal Article[ptyp] AND English[lang])

*muscle fatigue[Title/Abstract] AND work-related musculoskeletal disorders[Title/Abstract] AND (Journal Article[ptyp] AND English[lang])

*muscle fatigue[Title/Abstract] AND repetitive movements[Title/Abstract] AND (Journal Article[ptyp] AND English[lang])

*muscle fatigue[Title/Abstract] AND repetitive work[Title/Abstract] AND (Journal Article[ptyp] AND English[lang])

*muscle fatigue[Title/Abstract] AND assembly work[Title/Abstract] AND (Journal Article[ptyp] AND English[lang])

*muscle fatigue[Title/Abstract] AND low-force work[Title/Abstract] AND (Journal Article[ptyp] AND English[lang])

*muscle fatigue[Title/Abstract] AND low-intensity work[Title/Abstract] AND (Journal Article[ptyp] AND English[lang])

*muscle fatigue[Title/Abstract] AND low-load work[Title/Abstract] AND (Journal Article[ptyp] AND English[lang])

*muscle fatigue[Title/Abstract] AND work cycle time[Title/Abstract] AND (Journal Article[ptyp] AND English[lang])

*muscle fatigue[Title/Abstract] AND wrist[Title/Abstract] AND (Journal Article[ptyp] AND English[lang])

*muscle fatigue[Title/Abstract] AND work rest pattern[Title/Abstract] AND (Journal Article[ptyp] AND English[lang])

*muscle fatigue[Title/Abstract] AND rest breaks[Title/Abstract] AND (Journal Article[ptyp] AND English[lang])

*muscle fatigue[Title/Abstract] AND work duration[Title/Abstract] AND (Journal Article[ptyp] AND English[lang])

*muscle fatigue[Title/Abstract] AND work pace[Title/Abstract] AND (Journal Article[ptyp] AND English[lang]) *muscle fatigue[Title/Abstract] AND job rotation[Title/Abstract] AND (Journal Article[ptyp] AND English[lang])

*muscle fatigue[Title/Abstract] AND task design[Title/Abstract] AND (Journal Article[ptyp] AND English[lang])

Search strategy used in Scopus:

*TITLE-ABS-KEY(muscle fatigue AND upper limbs) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

*TITLE-ABS-KEY(muscle fatigue AND forearm muscles) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

*TITLE-ABS-KEY(muscle fatigue AND workload) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

*TITLE-ABS-KEY(muscle fatigue AND work-related musculoskeletal disorders) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

*TITLE-ABS-KEY(muscle fatigue AND repetitive movements) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

*TITLE-ABS-KEY(muscle fatigue AND repetitive work) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

*TITLE-ABS-KEY(muscle fatigue AND assembly work) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

*TITLE-ABS-KEY(muscle fatigue AND low-force work) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

*TITLE-ABS-KEY(muscle fatigue AND low-intensity work) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

*TITLE-ABS-KEY(muscle fatigue AND low-load work) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

*TITLE-ABS-KEY(muscle fatigue AND work cycle time) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

*TITLE-ABS-KEY(muscle fatigue AND wrist) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

*TITLE-ABS-KEY(muscle fatigue AND work rest pattern) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

*TITLE-ABS-KEY(muscle fatigue AND rest breaks) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

*TITLE-ABS-KEY(muscle fatigue AND work duration) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

*TITLE-ABS-KEY(muscle fatigue AND work pace) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

*TITLE-ABS-KEY(muscle fatigue AND job rotation) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

*TITLE-ABS-KEY(muscle fatigue AND task design) AND NOT patients AND NOT sports AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English"))

Search strategy used in Web of Science:

*(TS=(muscle fatigue AND upper limbs) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND forearm muscles) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND workload) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND work-related musculoskeletal disorders) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND repetitive movements) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND repetitive work) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND assembly work) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND low-force work) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND low-intensity work) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND low-load work) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND work cycle time) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND wrist) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND work rest pattern) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND rest breaks) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND work duration) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND work pace) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND job rotation) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND task design) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND upper limbs) NOT TS=patients NOT TS=sports) AND Idioma: (English)

*(TS=(muscle fatigue AND assembly work) NOT TS=patients NOT TS=sports) AND Idioma: (English)

Appendix F: Operationalization of the methodological quality assessment

Criteria

Study design

1. Positive if the duration and schedule of measurements were clearly described;
2. Positive if the tasks tested were clearly defined.

Participants

3. Positive if eligibility criteria and methods of selection of participants were clearly described.

Variables

4. Positive if the exposure to temporal aspects or task rotation schemes tested were clearly described (*independent variables*);
5. Positive if the variables to assess fatigue were clearly defined (*dependent variables*);
6. Positive if the method of variables analysis was clearly described.

Data sources/measurements

7. Positive if the methods of assessment were clearly described.

Bias

8. Positive if any efforts to address potential sources of bias were described, in particular:
   a. Adequate data collection and processing of fatigue measures (namely, for quantitative measures of fatigue) and;
   b. Control confounders introduce by participants during trials (e.g. give visual feedback, verbal encouragement, training).

Descriptive data

9. Positive if at least 2 of the following 3 elements were reported:
   a. Age (mean (SD) or range);

b. Gender (number, percentage or both);

c. Anthropometric measures (stature, weight or BMI).

Outcome data

10. Positive if the measures over time were clearly described.

Limitations

11. Positive if the limitations related to experimental protocol or participants were clearly described.

Generalizability

12. Positive if the external validity of results were discussed.