Physical Fatigue at Work: Prevalence and Interventions

by

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A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
August 3, 2019

Keywords: Fatigue Management, Cross-sectional Survey, Systematic Review, Market Basket Analysis, PEDro Scale, and Clinical Trial

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Abstract

Advanced manufacturing has resulted in significant changes on the shop-floor, influencing work demands and the working environment. The corresponding safety-related impacts, including fatigue, have not been fully captured on an industry-wide scale. The objectives of this dissertation are to understand the current state of workers' physical fatigue in the manufacturing sector, and suggest evidence-based interventions that can be applied at workplaces.

Specifically, these objectives were investigated through two studies. In the first study, a cross-sectional survey of U.S. manufacturing workers was conducted and analyzed to examine the prevalence of fatigue, its root causes and significant associated factors, as well as the individual fatigue coping methods adopted by survey participants. This study has been disseminated to the research community through a journal paper. The second study was a systematic review of existing controlled clinical trials to grade the methodological quality of the studies and assess the levels of evidence on interventions. Overall, this research aims to inform the design of fatigue monitoring and mitigation strategies as well as suggest future research related to fatigue development.

Acknowledgments

First, I would like to express my sincere gratitude to my advisors Dr. Fadel Megahed, and Dr. Lora Cavuoto, for their guidance, support, patience, and admirable trust in me through my whole doctoral journey. I would also like to thank my co-chair, Dr. Richard Sesek, and my committee members, Dr. Sean Gallagher and Dr. Pei Xu for their comments and perspectives on this work and continued help in my Ph.D. career. Similarly, I would like to thank my university examiner, Dr. JoEllen Sefton, who offered valuable suggestions for my dissertation.

In addition, I would like to thank the faculty members in the Department of Industrial and Systems Engineering, in particular Dr. Mark Schall and Mr. Tom Devall for their helpful advice in the survey design. I am also thankful to Dr. Alexander Vinel, Dr. Jerry Davis and Dr. Jorge Valenzuela for their kind support when my advisor was not at Auburn University. Much appreciation goes towards the staff who were all paramount to the completion of my degree.

I would like to present special thanks to Dr. James Barth from the Department of Finance for supporting me to step into more enriched research areas. I also hope to give my thanks to Dr. Chetan Sankar, my master degree advisor from the Department of Systems and Technology for all the training opportunities and feedbacks he provided.

I hope to thank the members of this ASSIST project, Dr. Ying-Ju Chen, Dr. Zahra Maman and Dr. Amir Baghadi, for their feedback and cooperation in conducting the systematic review.

To my family: Thank you for your unconditional love, support and trust. You encouraged me to follow my dream of pursuing a Ph.D. and never doubted my ability to succeed.

To my friends: This journey would not have been possible without your encouragement and companionship. Jinjin and Minghong, thank you for being there for me. Yu, thank you for your endless support and trust in me. Without you, I could have never made it, and never been able to withstand being far away from home. You are the best and will always be family.

To the universe: Thank you for all the positive vibrations that nourish me.

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Chapter 1

Introduction

1.1 Background

The term “fatigue” is used to describe a number of different, sometimes interrelated, phenomena. Specifically, it may be used to refer to: (a) lack of sleep, where it is utilized to capture “tiredness” (Shen et al., 2006); (b) whole body physical fatigue that includes cardiovascular fatigue (Davila et al., 2010); (c) localized muscle fatigue, as defined by Chaffin (1973); (d) mental fatigue/exhaustion, which was defined by van der Linden et al. (2003) “as a change in psychophysiological state due to sustained performance”, and (e) symptoms associated with a number of medical alignments that include Cancer, Parkinson’s Disease, Depression and Multiple Sclerosis (Dittner et al., 2004; Shen et al., 2006). Fatigue has no universal definitions based on its multidimensional nature. (Shen et al., 2006; Cavuoto and Megahed, 2016). From a workplace perspective, fatigue is linked to impaired/reduced performance as described in Brown (1994); Dittner et al. (2004); Barker and Nussbaum (2011b); Yung (2016); Yildiz et al. (2017); Filtness and Naweed (2017). Thus, in this research, fatigue denotes “a lower level of strength, physical capacity, or performance as a result of work activities”. “Strength” and “physical capacity” were integrated into the definition since they are important to physical work tasks. Note that both “capacity” and “performance” were included in the definition of fatigue that came from the Center of Research Expertise for the Prevention Of Musculoskeletal Disorders (CRE-MSD) Workshop, Toronto (Yung, 2016).

Fatigue is a known precursor to a number of negative outcomes. From a health perspective, fatigue has significant short-term and long-term implications. Some of the short-term implications include: discomfort (Björklund et al., 2000), lowered strength (Côté et al., 2005), and reduced motor control (Huysmans et al., 2010). In a workplace setting, these short-term symptoms result in "reduced performance, productivity, quality of work and increased incidence of labour accidents and human errors" (Yung et al., 2014, p. 1562). Perhaps, more importantly, fatigue has been hypothesized to contribute to several long-term health outcomes, including: (a) the occurrence of musculoskeletal disorders (Iridiastadi and Nussbaum, 2006; Naranjo-Flores and Ramírez-Cárdenas, 2014), (b) the development of chronic-fatigue syndrome (Fukuda et al., 1994), and (c) diminished immune function (Kajimoto, 2008). From a workplace point of view, Ricci et al. (2007) reported that fatigued workers report health-related lost productive time more than twice as often as those without fatigue. It is estimated that these short-term and long-term fatigue outcomes cost U.S. employers \$136 billion annually (Ricci et al., 2007).

1.2 Objectives

Given the reported negative consequences of fatigue, a large number of studies have attempted to measure the prevalence of fatigue in the workplace (often focusing on specific industries). In a population of 28,902 working adults (all occupations), Ricci et al. (2007) conducted a survey of U.S. workplaces and reported that 37.9% of the respondents had suffered from fatigue in the past two weeks. A high prevalence of fatigue has also been reported in Canada (Yung, 2016), the EU (Loriol, 2017), Japan (Kajimoto, 2008) and Sweden (Evengård, 2008). Based on a meta-analysis of the fatigue research pertaining to shift workers (all countries), Richter et al. (2016, p. 1) estimate that "90% of shift workers report regular fatigue and sleepiness at the workplace." Understanding the prevalence of fatigue in a given industry is an important first step towards identifying systematic interventions, policies and/or guidelines. Thus, in this research we surveyed U.S. manufacturing companies to assess the prevalence of fatigue, its drivers and how workers attempt to manage it.

There are potentially two main differentiators across industries: (a) how fatigue affects public interests (i.e., consider the number of people who witness or are impacted by fatigued employees in each of these domains), and (b) the degree of uniformity of the tasks within an industry (e.g., consider the difference between manufacturing and truck operators, where manufacturing presents a diverse set of jobs from welding, CNC operators, assembly line workers, manual material handlers, etc.). Recently, there are several indicators impacted by these two differentiators (at least in the US). First, federal investments using taxpayer dollars reflect a significant shift in the public's interest in manufacturing operations (Zients and Holdren, 2016). Second, the literature suggests that job duties, workload, and task repetition have been altered by advanced manufacturing technologies. We have limited information of the corresponding state of worker fatigue in advanced manufacturing environments. This is an important gap that needs to be addressed.

Several interventions have been designed to lower the injury risks and lost productivity associated with fatigue. The National Occupational Research Agenda (NORA) in the manufacturing sector highlights a need for intervention-effectiveness research (evidence-based intervention) including "research on the role of the organization of work on occupational safety and health outcomes, protective technologies, and safety culture" (Council, 2018). The NORA for Musculoskeletal Health also states the "adoption of these interventions by employers is slow" (National Occupational Research Agenda for Musculoskeletal Health, 2018).

A first step towards addressing this NORA objective is to review and assess the existing clinical trials for workplace interventions targeting physical fatigue. In our estimation, there are no published reviews that examine the quality of these studies and the efficacy of physical fatigue interventions in occupational settings. We did not review mental and sleep-related fatigue interventions since they have been examined in domain-specific reviews for the transportation (Rosekind et al., 1996; Caldwell, 2001) and nursing (Tiesinga et al., 1999; Steege et al., 2017) sectors.

To summarize, two specific objectives were investigated in this dissertation:

- Examine prevalence of fatigue, its root causes and significant associated factors, and the adopted individual fatigue coping methods in the manufacturing sector.
- Review of existing controlled clinical trials, grade the methodological quality of the studies and assess the levels of evidence on interventions.

1.3 Dissertation Overview

The remainder of this dissertation is organized as follows: In Chapter 2, a cross-sectional study surveyed U.S. manufacturing workers for the prevalence of fatigue, its root causes and significant factors, and adopted individual fatigue coping methods. Frequent combinations of fatigue causes and individual coping methods were identified. Note that this study was published in Applied Ergonomics in June 2017. Chapter 3 presents a systematic literature review on workplace physical fatigue interventions, focusing on evaluating the methodological quality and the strength of evidence. Chapter 4 summarizes the contribution of this research and discusses the directions of future studies in fatigue management. The appendices contain supplementary materials regarding the survey, the datasets and the analysis methods in both studies.

Chapter 2

A survey of the prevalence of fatigue, its precursors and individual coping mechanisms among U.S. manufacturing workers

2.1 Introduction

The manufacturing sector is an important contributor to the U.S. economy, accounting for 14% of the Gross Domestic Product (GDP) and 11% of total employment (Economic Development Partnership of Alabama, 2012). Since 2011, the U.S. government has made significant investments in *advanced manufacturing*, which is a subset of manufacturing activities that relies on the use of automation, computation and sensing technologies. The President's Council of Advisors on Science and Technology (2011, p. i) describes advanced manufacturing activities as "... [involving] both new ways to manufacture existing products, and the manufacture of new products emerging from new advanced technologies". According to The White House (2016), the transition to advanced manufacturing has commenced in the United States, and it has started to impact many manufacturing industries.

With this transition, it is important to understand how the role of labor is changing based on advanced manufacturing. First, advanced manufacturing, which is also related to Industry 4.0 (i.e., the current trend of automation and data exchange in manufacturing technologies) (Lee et al., 2015; Spöttl, 2017), is different from the computer-integrated manufacturing approach of the 1980s and early 1990s. Specifically, the end goal of computer-integrated manufacturing is a workerless manufacturing environment (i.e., lights out manufacturing facilities). Advanced manufacturing, however, aims to integrate workers into the cyber-physical infrastructure to maximize the impact of their skills (Gorecky et al., 2014). Second, it is well documented that automation can lead to: (a) reducing repetitive, mundane and dangerous work (Kelly, 2012;

Thompson, 2014; Yakowicz, 2016); (b) increasing the dependency on multi-skilled workers who can simultaneously work multiple workstations, which originated with the creation of U-shaped cells in lean manufacturing (Black and Phillips, 2013) and became more prominent with automation (Ferjani et al., 2017); and (c) the broadening of workers' autonomy and responsibility as well as requiring new job duties (Waldeck, 2014). Third, advancements in computation and sensing technologies are leading to smart factories, where workers will respond to the demand for mass-customized products (Hu, 2013) and must be capable of processing and acting upon large amounts of information.

Based on these new demands, the transition to advanced manufacturing can potentially increase both the physical and mental workload on workers. There is an increasing amount of literature suggesting that the increased workloads contribute to the higher prevalence of fatigue, and continue to be a factor in advanced manufacturing settings (Brocal and Sebastián, 2015; Romero et al., 2016; Ferjani et al., 2017; Gust et al., 2017).The changing nature of jobs in the emerging era of advanced manufacturing requires a holistic analysis of the workers' states from an occupational health and safety perspective. This is especially important as there is limited information on the role of ergonomists and safety engineers in designing these jobs and managing the increasing workload in advanced manufacturing environments.

In this study, the impact of these changes on U.S. manufacturing workers is examined in an attempt to answer the following research questions:

- What is the prevalence of fatigue among U.S. advanced manufacturing workers?
- What are the main drivers for fatigue?
- What are the coping measures of workers in combating fatigue?

These questions aim to understand fatigue prevalence from a macro-level among manufacturing workers (i.e., not about whether a worker is fatigued at a particular moment but rather over the span of their typical work week). To answer these questions, an online questionnaire was created targeting U.S.-based manufacturing employees. To our knowledge, this survey represents the first nationwide study that aimed to evaluate and assess the prevalence of fatigue, its drivers and how workers attempt to manage it within U.S. manufacturing companies. Understanding these three aspects are important in designing manufacturing and advanced manufacturing workplaces that are centered around human workers.

2.2 Methods

2.2.1 Participants

In order to survey the prevalence of fatigue, its drivers, and individual coping mechanisms among U.S. manufacturing workers, we constructed an online survey (detailed in Section 2.2.2). Workers currently employed in manufacturing industries and aged 19 or older were invited to participate. They were recruited through two main channels: (a) emails that were sent to over 25 manufacturing company contacts, who were asked to share the survey link to their employees; and (b) survey invitation emails that were sent through the membership list of several American Society of Safety Engineers (ASSE) listservs (NOTE: ASSE is now ASSP - the American Society of Safety Professionals). In total, we have sent 38 emails to safety professionals asking their assistance to share our survey with their manufacturing employees.

Our recruitment strategy was based on three main propositions. First, our manufacturing company contacts were more likely to forward our survey links to their employees. Second, our contacts worked in organizations whose factories were primarily located in the Midwestern, Southern, and Southeastern regions of the U.S. These correspond to the three largest hubs of U.S. manufacturing activities according to recent reports by the Economic Policy Institute (Scott, 2015) and Forbes (Kotkin and Shires, 2015). This means that a large number of respondents should be from these important regions. Third, the utilization of the ASSE listservs allowed us to reach a large number of U.S. safety professionals. While we expect a lower response rate from these professionals, respondents from this group present the opportunity to reduce the impact of any pre-selection bias (of company types) on our study and diversify the regions from which our participants are selected.

2.2.2 Survey Design and Procedure

This survey was designed as a cross-sectional study, which aims to examine the three major questions listed in Section 2.1. To address these research questions, the survey collected data on:

(A) Demographics of the respondents. This included questions on each participant's age, sex, height and weight. These variables have been shown to be potential risk factors for fatigue occurrence/development (Akerstedt et al., 2004; Yamazaki, 2007; Amasaka, 2007; Arellanoa et al., 2014).

(B) Fatigue-related individual characteristics. Specifically, there were questions pertaining to the amount of sleep (Lerman et al., 2012; Arellanoa et al., 2014), smoking (Corwin et al., 2002; Wüst et al., 2008), alcohol intake (Dawson and Reid, 1997), exercise frequency (Samaha et al., 2007) and experience / duration of employment in their present positions, which were shown to be important factors associated with fatigue in earlier studies.

(C) Work-related exposures. These were divided into two types of questions. The first set of questions pertained to the frequency of doing certain tasks; for example, repetitive assembly, equipment operations, overhead work and material handling. These were on visual analog scales (VAS). The second set was related to the number of hours worked and their distribution between sitting, standing and walking each day.

(D) Worker perceived fatigue causes. Each respondent was asked to identify, from a list, which aspects of work contributed most to fatigue. The question asked the respondent to "Select all that apply", while allowing for adding additional causes. Fifteen items were on this list, which were categorized by survey constructs (workers, work environment, work): lack of sleep (Lerman et al., 2012), lack of energy, lack of exercise and feel sick/ill; lack of caffeine, feeling of not being respected (De Croon et al., 2002; Mocci et al., 2001), work stress (Åkerstedt et al., 2002; Dahlgren et al., 2005), shift schedule (Åkerstedt et al., 2002), lack of water and poor work environment (e.g., temperature, light, workspace) (Melamed and Bruhis, 1996); fast pace of work (Harrell, 1990; Bosch et al., 2011), insufficient rest breaks (Tucker, 2003; Kopardekar and Mital, 1994;

Dababneh et al., 2001), heavy work loads (Åkerstedt et al., 2002; De Croon et al., 2002; Dahlgren et al., 2005), lots of movement required, and high levels of walking.

(E) Perceived fatigue level, frequency and interference. These are the outcome variables of interest, and the related questions were adapted from the Fatigue Symptom Inventory (FSI). Specific items include: (a) Rate your level of fatigue on the workday you felt most fatigued in the past week; (b) How often do you feel fatigued as a result of your work; and (c) Rate how much, in the past week, the fatigued interfered with your normal work activity. Table 2.1 presents an overview of some of the most often used fatigue scales and questionnaires in fatigue assessment.

(F) Body parts affected. We presented 11 body parts/locations and asked each respondent to answer on a VAS scale the frequency for which each location was fatigued. These questions are informative in the context of localized fatigue measurement. The eleven body parts covered from head to ankle or feet were adapted from the affected body parts by nonfatal injuries and illnesses based on the report of Bureau of Labor Statistics (2015).

(G) Individual fatigue coping mechanisms. Each respondent was asked a “Select all that apply” question on their recovery approach. The given fatigue recovery methods include drink caffeinated beverages (Davis et al., 2003; Lorist and Tops, 2003), consume energy drinks (Howard and Marczinski, 2010; Kennedy and Scholey, 2004), take medicines (legal/illegal) (Lerman et al., 2012), have snack bars, listen to music (Choi, 2010), talk with coworkers, add a stool, increase air flow, stretch the body / do exercise and one add item option that allowed for adding other coping measures.

This survey was initially constructed by the authors considering different aspects of risk factors suggested from the Maastricht Cohort Study of “Fatigue at Work” (Kant et al., 2003). It was revised based on feedback solicited from two faculty and three safety managers in manufacturing workplaces. The study was approved by the Institutional Review Board at Auburn University, and all participants provided an informed consent before participating. Survey invitation emails described the survey content and directed participants to an online survey (available at https://auburn.qualtrics.com/jfe/form/SV_dakGAN9cWJwFCtL, see Appendix A). The

Table 2.1: Differences between Our Survey and Existing Fatigue Scales, Questionnaires and Surveys in the Literature

Scale	**Type of fatigue**	**What is being assessed**	**Target Population**	**Time Frame**	**# Items**	**Type of Scale**	**Unattended Completion**
FSS Krupp et al. (1989)	Physical, psychological	Impact, functional outcomes	MS & SLE patients	Past 2 weeks	9	7-point Likert	No
GVA Monk (1989)	Mood	Severity	Psychiatric patients	Now	8	Visual analogue	No
PE/ME Wood et al. (1990)	Physical, mental	Severity	Healthy volunteers	End of week	2	Visual analogue	Yes
VAS-F Lee et al. (1991)	General, physical mental	Severity	General medical	Now	18	Visual analogue	Yes
FAI Schwartz et al. (1993)	General	Phenomenology, severity, impact, triggers	General medical	Past 2 weeks	29	7-point Likert	No
MAF Belza et al. (1993)	General	Severity, impact, distress, timing	Rheumatoid arthritis	Past week	16	Visual analogue	No
CIS Vercoulen et al. (1994)	General, physical cognitive	Phenomenology, severity	Chronic fatigue	Past 2 weeks	20	7-point Likert	No
MFI Smets et al. (1995)	General, physical mental	Phenomenology, severity, impact	General medical	Previous days	20	7-point Likert	No
FIS Fisk et al. (1994)	Physical, psychosocial cognitive	Impact	MS patients	Past month	40	5-point Likert	No
FSI Hann et al. (1998)	General	Severity, impact, duration	Cancer patients	Past week	14	11-point Likert	Yes
MFSI Stein et al. (1998)	Global, physical, mental, emotional	Phenomenology, severity	Cancer patients	Past week	30	5-point Likert	No
SOFI Åhsberg (2000)	Physical, psychological	Phenomenology, severity	Working population	Now/End of work	20	7-point Likert	No
OFER Winwood et al. (2005)	Mental, physical, chronic, acute	Phenomenology, severity	Working population	Past few months	15	7-point Likert	Yes
FAS Shahid et al. (2011)	Physical, mental	Phenomenology, severity	Sarcoidosis patients	Now/End of work	10	5-point Likert	No
CFQ Jackson (2015)	Physical, psychological	Phenomenology, severity	Working population	Past month	11	4-point Likert	No
This Study	General, physical	Severity, impact	Manuf. workers	Past work week	4	Visual analogue	Yes

FSS: Fatigue Severity Scale, GVA: Global Vigor and Affect, PE/ME: Physical Energy and Mental Energy, VAS-F: Visual Analog Scale for Fatigue,
FAI: Fatigue Assessment Instrument, MAF: Multidimensional Assessment of Fatigue, CIS: Checklist Individual Strength, MFI: Multidimensional Fatigue Inventory,
FIS: Fatigue Impact Scale, FSI: Fatigue Symptom Inventory, MFSI: Multidimensional Fatigue Symptom Inventory, BFI: Brief Fatigue Inventory,
SOFI: Swedish Occupational Fatigue Inventory, OFER: Occupational Fatigue Exhaustion/Recovery Scale, MS: Systemic lupus erythematosus
FAS: Fatigue Assessment Scale, CFQ: Chalder Fatigue Scale, SLE: Systemic Lupus Erythematosus

Adapted from Dittner et al. (2004)

survey was created using Qualtrics Survey Software (2016). Data collection occurred between mid-February to early May in 2016.

2.2.3 Data Analysis

The analysis of the data captured in this survey is divided into four components. First, we analyze the demographics of our respondents and their job characteristics. Then, we examine how the responses contribute to answering the three main research questions behind this survey. IBM SPSS Version 23 (2016) was primarily used for the analysis for all four components. In the subsections below, we briefly discuss these four components.

Demographics of Survey Respondents and Characteristics of their jobs

This component captures data categories (A)-(C) from Section 2.2.2. The related survey questions result in either a categorical response (e.g., sex, smoking, and alcohol intake) or a continuous measure (e.g., height and weight). We computed means and standard deviations for continuous variables, and reported percentages to capture the frequency of categorical variables selected by the respondents.

The Prevalence of Fatigue among Manufacturing Workers

To address this research question, it is important to first define what is considered "fatigued" versus "not-fatigued" based on the outcome variables (see Category E in Section 2.2.2). Without a true label, Gibbs Sampling can be used to estimate the parameters of mixture distributions (Diebolt and Robert, 1994). This means that it can be used to estimate the not-fatigued and fatigued distributions of VAS scores on the "Most Fatigued Level" (MFL) outcome. Based on the Gibbs Sampling for a mixture of normal distributions, the not-fatigued and fatigued distributions had an estimated mean VAS scores at 6.87 and 70.36, respectively. We selected the cut-off at VAS = 20. Based on our cut-off and the estimated parameters for the two normally-distributed populations: (a) 99% of individuals from the fatigued population would fall above our cut-off, and (b) 99% of individuals from the non-fatigued population would fall below our cut-off value. Thus, from this discussion, an estimate for the percentage of *fatigued workers* can be computed based on: $\frac{\text{Number of respondents whose VAS for the outcome} > 20}{\text{Total number of respondents (i.e. } n = 451)}$. In this study, we use the MFL (over the past week) as the primary fatigue outcome. Note that we chose the MFL results for our discussion since Fatigue Symptom Inventory (FSI) scoring indicates that each item on the FSI can be scored as an individual scale, providing the information about that variable. We also find that the MFL measurement is very consistent with the other two fatigue outcomes (with Cronbach's alpha as .891) and MFL could represent the worst case fatigue scenario.

We present the summary statistics for the body parts affected for fatigued participants using the VAS $= 20$ cut-off for the MFL to categorize our participants into fatigued and not-fatigued. In addition, independent samples t-tests were used to identify mean differences between not fatigued ($MFL \leq 20$) and fatigued ($MFL > 20$) individuals for each body location. This analysis can provide some data-driven insights pertaining to the consistency of respondents in answering our VAS questions. In particular, it is expected that fatigued respondents will, on average, have higher values of "fatigued" for the body locations when compared to the "not-fatigued" group.

Main Drivers of Fatigue

Two analyses can provide insights into the drivers of fatigue by focusing on the respondents who were deemed fatigued. First, we can evaluate their responses for: workers perceived causes of fatigue (i.e., Category (D) in Section 2.2.2). Note that we have used a "Select all that Apply" question for the worker's perceived root-causes. Therefore, we present the percentages of fatigued workers that selected each category. This analysis is somewhat limited, however, since it does not provide insights into which categories are likely to happen in combination. To overcome this limitation, we use Market Basket Analysis, which is a well known data-mining method for analyzing the occurrence of frequent item sets in transactional data (Han et al., 2011; Leskovec et al., 2014). To briefly explain the concepts behind Market Basket Analysis, let the set of responses for "fatigued" participants be defined as Ω. To simplify the explanation, we will limit our analysis to only two causes (say A and B). Let us define R_A to be the set of responses containing cause A. Then, the support for A can be computed as:

$$Supp(A) = \frac{\text{Number of respondents who selected A}}{\text{Total number of fatigued respondents}}. \tag{2.1}$$

To make the notation concise, let us denote the numerator and denominator in the above equation, by: E_A and n_f, respectively. The term confidence (not in the statistical fashion) is used to denote the following:

$$Conf(A \rightarrow B) = \frac{E_A}{E_B} = \frac{\text{Number of respondents who selected A}}{\text{Number of respondents who selected B}}. \tag{2.2}$$

Note that high values for both the support and confidence are not sufficient for ensuring that a relationship between A & B is interesting. Lift is a measure used to capture whether such a relationship is interesting or not. Lift(A $\rightarrow$ B) $>$ 1 if and only if the selection of A is increases the probability that B is also selected by the respondent. In this study, we use SAS Enterprise Miner to perform the market basket analysis. We only report the results which meet the following conditions: $Supp \geq 0.10$, $Confidence \geq 0.5$, and $Lift \geq 1$. Therefore, the *market basket analysis* approach will ensure that we present only the relationships where the inclusion of a cause, or a set of causes, increases the likelihood of another cause to be selected. Han et al. (2011) and Leskovec et al. (2014) explain Market Basket Analysis as a data mining method to identify frequent itemsets.

In the second analysis, we conduct a bivariate analysis between the reported individual characteristics and exposures (i.e. Categories (A)-(C) of Section 2.2.2) against the dichotomized “Most Fatigue Level” outcome. For each categorical variable in (A)-(C), mutually unadjusted odds ratios (ORs) was calculated to measure the association between the variable and the dichotomized fatigue outcome. An independent samples t-test was conducted for each continuous variable to identify their mean difference between the fatigued and not-fatigued groups. Significance is determined based on 95% confidence interval of the ORs (does not contain one) or mean difference (does not contain zero).

Overview of Individual Coping Measures

Individual coping measures are captured through “Select All that Apply” questions. Thus, to understand which individual coping measures are most frequently used, we: (a) present the selection percentages for each measure; and (b) perform Market Basket Analysis to examine if the selection of any measure by a participant can result in an increased likelihood of the utilization of additional coping measure(s).

2.3 Results

2.3.1 Demographics of Survey Respondents and Characteristics of their Jobs

There were 807 individuals that accessed the online survey as of May 7^{th}, 2016 ($\approx$ 2 months since our first survey invitation email was sent out). The survey was completed by 451 individuals (a completion rate of 55.9%). The number of completed surveys exceeded our target of 385 completed surveys, which is the minimum number of participants required to achieve the margin of error to be at lower or equal than 5%, and the confidence level is at least 95%. Only the completed surveys were included in our analysis, which means that $n = 451$ for all our risk factors and outcome variables. Table 2.2 provides a summary of the respondents' demographics and their fatigue-related individual characteristics.

Table 2.2: The Demographics of Respondents and their Fatigue-related Individual Characteristics ($n = 451$).

(A) Demographics of the Respondents		
Variable	**Mean (SD)**	**%**
Age (yr)	48.3 (10.1)	–
Sex		
Male	–	82
Female	–	18
Height (ft)	5.8 (0.3)	–
Weight (lb)	210.2 (40.9)	–
Body Mass Index (BMI) (kg/m^2)	30.3 (5.3)	–
Obesity Categories		
Normal Weight ($18.5 < BMI \leq 25kg/m^2$)	–	12.4
Overweight ($25 < BMI \leq 30kg/m^2$)	–	41.2
Obese (BMI $> 30kg/m^2$)	–	46.3

(B) Fatigue-Related Individual Characteristics		
Variable	**Mean (SD)**	**%**
Cigarette Use		
No	–	92.5
Yes	–	7.5
Alcohol Use		
0-1 units per week	–	52.5
1-2 units per week	–	12
3-6 units per week	–	20
7-9 units per week	–	6.7
>9 units per week	–	8.9
Exercise Level		
Seldom	–	30.4
1 time per month	–	3.8
1 time per week	–	18
3 times per week	–	32.6
Daily	–	15.3
Experience Level		
$\leq$ 6 months		5.8
7-12 months	–	5.1
1-5 years	–	33.7
5-10 years	–	14.4
>10 years	–	41
Sleep Quantity (hr)	6.2 (1.1)	–

The mean and standard deviation (SD) are reported for continuous variables. Percentages (%) are reported for categorical variables.

Table 2.3 presents descriptive statistics for the respondents' workplace related exposures and a summary of the VAS values for the major outcomes. There are three main observations that can be made from the table. First, among the outcomes, the highest mean value was for "Most Fatigued Level" and the lowest mean value was for "Fatigue Impact on Work". This means that, on average, compared to the maximum fatigue levels respondents experienced (VAS = 44.8), the self-reported impact of fatigue on their work was less (VAS = 22.4). The level of "fatigue impact at work" was evaluated by asking subjects to "rate how much, in the past week, fatigue interfered with your normal work activity", which is an adaptation of Question 7 in the FSI (Krupp et al., 1989). Our definition intentionally removes the "(includes both work outside the home and housework)" from the FSI definition since we are targeting work performance while the FSI was originally designed for breast cancer patients. The second observation is that overhead work was the least frequent work-related exposure, which may suggest that the safety professionals at these plants are translating the recommendations from the literature to eliminate/reduce any tasks that require overhead work. The third observation is that an overwhelming majority of participants work overtime (> 40 hrs, 86.7%) and/or rotating shifts (61.2%). This result matches the results from a recent report by the U.S. Bureau of Labor Statistics which indicates that the average weekly overtime hours by manufacturing workers is 4.2 hours (Bureau of Labor Statistics, 2016b).

Table 2.3: Summary Statistics for Work related Exposures and Outcomes

(C) Work-related Exposures		
Variable	**Mean (SD)**	**%**
Repetitive Processing or Assembly	19.0 (31.1)	–
Equipment Operation	22.4 (34.6)	–
Overhead Work	12.6 (20.4)	–
Maintenance Activities	27.4 (37.5)	–
Manual Material Handling	22.9 (31.7)	–
Sitting hours at work	3.4 (2.7)	–
Standing hours at work	1.5 (1.6)	–
Walking hours at work	5.7 (2.9)	–
Working Overtime?		
No	–	13.3
Yes	–	86.7
Working a Rotating Shift Schedule?		
No	–	38.8
Yes	–	61.2

(D) Fatigue Outcomes	
Variable	**Mean (SD)**
Fatigue Frequency Level (FFL)	36.9 (31.8)
Most Fatigued Level (MFL)	44.8 (36.4)
Fatigue Impact at Work (FIW)	22.4 (26.0)

Units of variables: Frequency in conducting job tasks - percent of time spent in a particular task, duration of postures at work - hours, fatigue outcomes - VAS score.

2.3.2 The Prevalence of Fatigue among Manufacturing Workers

The Overall Prevalence of Fatigue

The prevalence rate of fatigue based on the “Most Fatigued Level” are provided. The prevalence of fatigue based on the “Fatigue Frequency” and the “Fatigue Impact on Work” are detailed in our supplementary materials.

A cut-off value of 20 was used to distinguish between “fatigued” and “not-fatigued” states. Based on this threshold and the reported results for the “Most Fatigued Level”, 260 workers (out of 451 respondents) were found to have been fatigued over the past month. Therefore, based on our survey, the prevalence of fatigue among U.S. manufacturing workers is approximately 57.9%. An analysis of the “Fatigue Frequency”, shown in the supplementary materials, presents an estimate that also exceeds the 55% margin. These estimates are larger than the 37.9% reported by Ricci et al. (2007) for all U.S. occupations (over the past two weeks). However, they are less than the 90% estimate for shift workers, across the world, reported by Richter et al. (2016).

Our estimates for fatigue indicate that at least half of the U.S. manufacturing workforce have experienced fatigue during the past week. In our estimation, this relatively large number (compared with the fatigue prevalence across industries such as 37.9% in Ricci et al. (2007)) can be potentially explained by a number of different factors. First, the transition to advanced manufacturing environments has generally resulted in increased workloads and job responsibilities on manufacturing workers (as highlighted in Section 2.1). From an ergonomics perspective, these elevated workloads are more likely to result in fatigue, especially if the redesigned jobs include limited input from safety professionals. Loriol (2017) presents several philosophical explanations of fatigue in contemporary working environments. For example, workers are subjected to an ever-demanding work environment that requires them to perform many tasks and roles. However, these workers often lack the flexibility to seek better employment opportunities elsewhere which means that they continue to work in difficult and fatiguing work environments. In our estimation, these explanations can also be used in helping understand how fatigue manifests in today’s manufacturing environments.

Affected Body Parts among the Overall Fatigued Workers

In addition to the overall fatigue ratings, workers were also asked to rate how often do they experience fatigue in several body parts during a typical workday. By focusing only on the fatigued workers (i.e., based on the Most Fatigued Level cut-off n_f=260), we can generate some insights pertaining to localized fatigue. In Figure 2.1, we summarize the frequency distribution of each body part being affected based on the VAS responses of the fatigued respondents. This box plot reveals that the: ankles or feet (51.5), lower back (50), eyes (50), shoulders (49), head (45) and neck (43) have higher median VAS values when compared to the other body locations, which indicate these body parts are impacted more often for our fatigued participants.

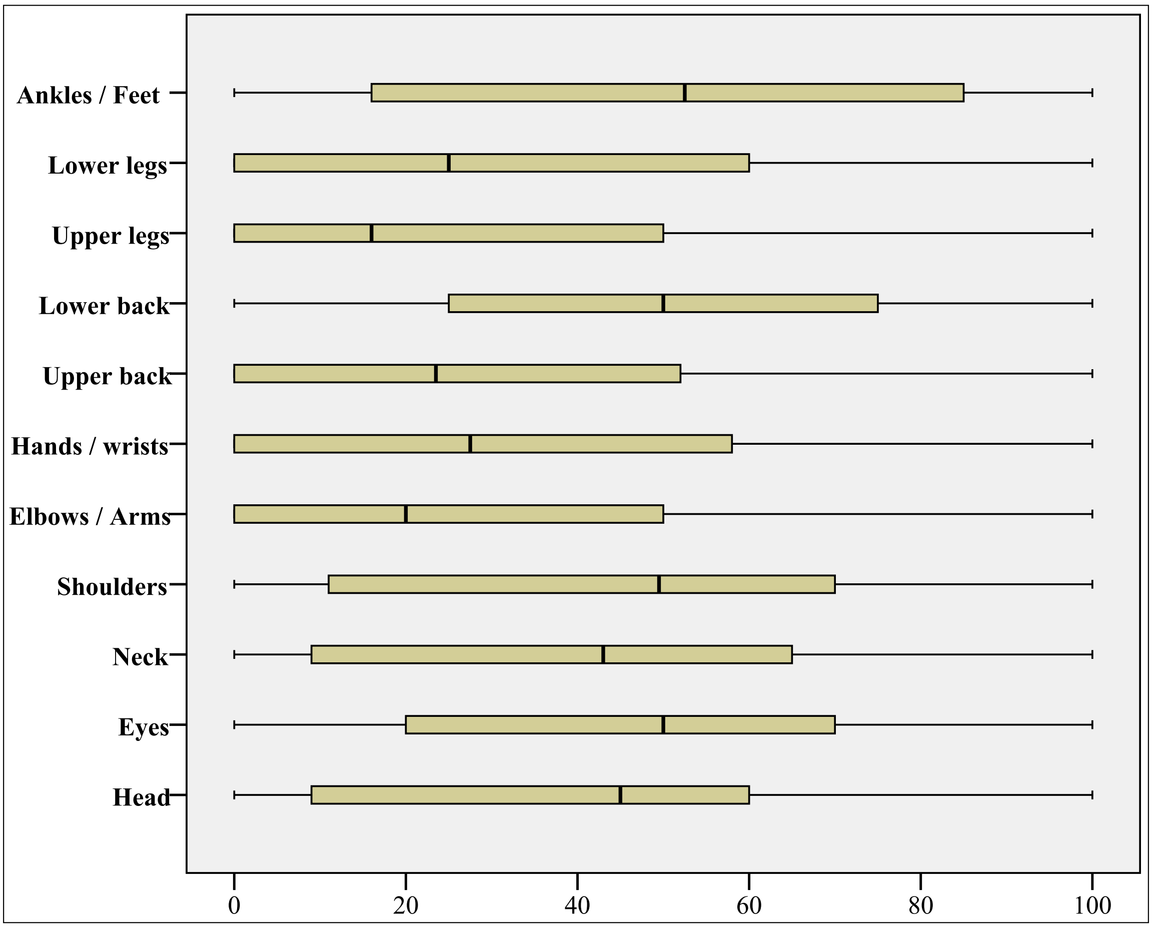

Figure 2.1: Frequency of Body Locations Affected for Fatigued Workers

We limit our discussion here to the top three body locations (ankles or feet, lower back and eyes). The self-reported high levels of walking (5.7 hrs/workday on average, Table 2.3) when compared to sitting and standing can help explain the high median VAS score for the ankles or feet. The literature has shown that prolonged walking activities are commonly associated with worker's complaints of foot/ankle pain and/or disorders (Werner et al., 2010; Reed et al., 2014). The back was often reported as the frequently injured part of body for nonfatal injuries and illnesses among manufacturing industry (Bureau of Labor Statistics, 2016a). Eye fatigue is related to the use of video display terminals in equipment operation and inspection activities (Lin et al., 2008; Mocci et al., 2001), which are features of advanced manufacturing processes based on our manufacturing experience (Megahed et al., 2011; Megahed and Camelio, 2012; Megahed et al., 2012; He et al., 2016).

Independent samples t-tests were also conducted on each affected body part between "fatigued" (MFL >20) and "not-fatigued" respondents (MFL ≤ 20). The mean differences of the VAS scores showed that not-fatigued workers experienced less impact on each body part compared to their fatigued counterparts. The statistically significant mean differences ranged from -22.887 (elbows and arms) to -45.299 (ankles and feet). In our estimation, these statistically significant differences across the different body locations indicate that the use of VAS was appropriate for the overall fatigue measurement. In addition, these results can also justify the use of Gibbs Sampling in obtaining the cut-off threshold as 20 in separating the overall fatigued and not-fatigued respondents. The efficacy of Gibbs Sampling and VAS is an expected result based on the literature presented in Sections 2.1 and 2.2.3.

2.3.3 Main Drivers of Fatigue

Perceived Root Causes for Fatigue

The percentage of fatigued participants who selected each root-cause is represented in Figure 2.2. The top three most frequently reported perceived fatigue causes are: lack of sleep, work stress and shift schedule based on the proportion of fatigued respondents who indicated these causes. Each of these causes was reported by more than 50% of the respondents, then there was a dropoff before the 4th and 5th highest responses of poor environment and high levels of walking.

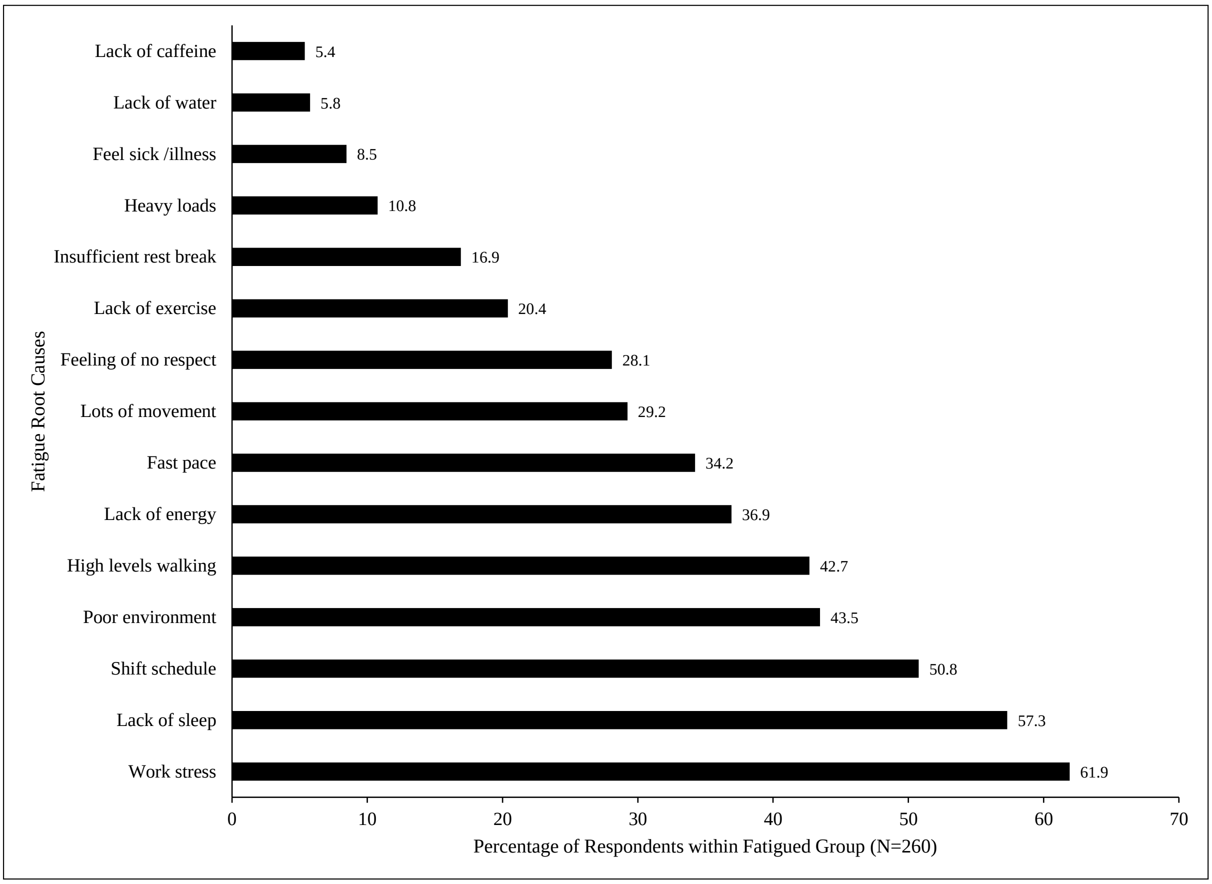

Figure 2.2: Percentage of Fatigued Respondents Selecting a Root-Cause

In addition to the percentage of each single reported cause, we use the Market Basket Analysis approach to identify which perceived causes were often selected in combination. This is especially important since it provides context to the results depicted in Figure 2.2. For example, are shift schedule and poor environment selections mutually exclusive or frequently selected in combination by respondents. The results from the Market Basket Analysis approach are presented in Table 2.4 (with the inclusion criteria detailed in Section 2.2.3).

Table 2.4: Market Basket Analysis for Fatigue Root Causes ($n_f = 260$).

Set / Frequent Bucket	**Support (%)**	**Confidence (%)**	**Lift**
Shift schedule, Lots of movement → High levels of walking	15.1	79.2	1.80
High levels of walking, Poor environment → Lots of movement	14.3	60.0	1.96
High levels of walking, Lack of sleep → Lots of movement	14.3	56.3	1.84
Insufficient rest break → Fast pace	12.3	70.5	1.99
High levels of walking, Fast pace → Lots of movement	11.5	61.7	2.02
Shift schedule, Lack of energy → Lack of sleep, Poor environment	11.5	50.0	1.85
High levels of walking, Lack of energy → Lots of movement	10.3	60.5	1.98
Lack of sleep, Fast pace → Lots of movement	10.3	54.2	1.77

The first association rule, which illustrates from a data-driven perspective the relationship between the selection of “shift schedule”, “lots of movement” and “high levels of walking”. The support indicates that 15.1% of our fatigued participants selected these three factors in combination. Recall, from Figure 2.2, shift schedule, lots of movement and high levels of walking were selected by 50.8%, 29.2%, and 42.7% of respondents, respectively. The confidence captures the conditional probability between the two sets, i.e., 79.2% of the respondents who selected shift schedule and lots of movement also picked high levels of walking. The lift means that the selection of high levels of walking is 1.80 times more likely when shift schedule and lots of movement are selected together when compared to being selected at random. The aforementioned logic can be applied to any row in Table 2.4. In general, the relationships in the table has a support $\geq$ 10.3%, confidence $\geq$ 54.2%, and a lift $\geq$ 1.77. Future prospective investigations may be required to examine these relationships in more detail.

Bivariate Analysis between Exposures and Fatigue

We conducted a bivariate analysis between dichotomized fatigue outcomes and several of the measured variables to identify fatigue-related risk factors. Table 2.5 presents the factors that were found to be significantly associated with this fatigue.

The mean age of fatigued workers was statistically significantly higher than not-fatigued workers (49.6 vs 46.5 years), and a greater proportion of fatigued workers have been in their current positions for over ten years (43.3% vs 37.9%), among the variables relating to demographics and individual fatigue related factors. These results indicate that fatigued workers have a higher odds of being older. This is in accord with the findings among CNC Lathe operators where age and duration of employment significantly affected perceived physical exertion (Arellanoa et al., 2014). Age was also found to be associated with vitality score among Japanese manufacturing workers (Yamazaki, 2007) and a similar positive association between age and fatigue were also discovered in studies of fatigue for pilots. (Bourgeois-Bougrine et al., 2003).

A higher percentage of fatigued respondents typically drank 3-6 alcohol units/week than not-fatigued respondents (24.1% vs 14.2%). As the effect of alcohol use has frequently been reported to interfere with worker circadian rhythms and subsequently affects sleep quality and

Table 2.5: Bivariate Analysis between Significant Exposures and Fatigue ($n = 451$).

Variables	**Total**	**Not Fatigued (0-20)**	**Fatigued (21-100)**	**Mean Difference or Odds Ratio (95% CI)**
Age	48.3 (10.1)	46.5 (10.2)	49.6 (9.9)	-3.185 (-5.064, -1.307)
Alcohol use				
0-1 unit	52.5	58.9 (47.3)	47.9 (52.7)	1
1-2 units	12	13.7 (48.1)	10.7 (51.9)	.965 (.534, 1.743)
3-6 units	20	14.2 (30.0)	24.1 (70.0)	2.091 (1.245, 3.509)
7-9 units	6.7	5.3 (33.3)	7.7 (66.7)	1.792 (.805, 3.991)
>9 units	8.9	7.9 (37.5)	9.6 (62.5)	1.493 (.750, 2.974)
Duration of employment in position				
<= 6 months	5.8	8.4 (61.5)	3.8 (38.5)	1
7-12 months	5.1	4.7 (39.1)	5.4 (60.9)	2.489 (.787, 7.870)
1-5 years	33.7	34.7 (43.4)	33.0 (56.6)	2.085 (.889, 4.891)
5-10 years	14.4	14.2 (41.5)	14.6 (58.5)	2.252 (.887, 5.716)
>10 years	41	37.9 (38.9)	43.3 (61.1)	2.511 (1.080, 5.837)
Hours of sleep	6.2 (1.1)	6.0 (1.1)	6.3 (1.1)	-.319 (-.520, -.118)
Work hours per week	50.8 (10.1)	52.0 (11.2)	50.0 (9.1)	1.987 (.103, 3.870)
Rotating shifts				
No	38.8	28.9 (31.4)	46.0 (68.6)	.366 (.241, .555)
Yes	61.2	71.1 (48.9)	54.0 (51.1)	1
Repetitive assembly or processing	19.0 (31.1)	5.6 (19.6)	28.8 (34.2)	-23.262 (-28.692, -17.831)
Equipment operation	22.4 (34.6)	3.4 (13.5)	36.3 (38.6)	-32.917 (-38.655, -27.180)
Overhead work	12.6 (20.4)	3.1 (11.9)	19.5 (22.5)	-16.370 (-19.886, -12.854)
Maintenance	27.4 (37.5)	5.2 (18.5)	43.5 (39.5)	-38.354 (-44.425, -32.282)
Material handling or lifting	22.9 (31.7)	5.3 (17.7)	35.9 (33.4)	-30.608 (-35.836, -25.380)

lead to fatigue with decreased work performance (Dawson and Reid, 1997), the positive association between alcohol use and fatigue is consistent with our expectations. Fewer fatigued workers worked in rotating shift schedules (54.0%) compared with not-fatigued workers (71.1%). This negative association between rotating shift work and fatigue appeared counterintuitive at first glance as rotating shift work could be related with irregular sleep patterns and fatigue (Niu et al., 2011). However, it should be noted that the fixed shifts included the early morning and night shift, and they have also been shown to be positively associated with fatigue (Åkerstedt and Landström, 1998; Åkerstedt, 2003). By cross tabulating between the frequency of conducting job tasks and the rotating shifts indicator, we found that rotating shift workers conducted overhead work, maintenance and manual material handling tasks less frequently than those worked in a fixed shift (the statistically significant mean differences for percentage of time spent in these three job tasks were -7.04%, -16.93%, -10.76%, respectively). From the fixed shift worker's perspective, though they did not work in rotating shifts, they also spent more time in the demanding work tasks, which could have a more dominant positive association with fatigue than rotating shifts. Fatigued workers spent greater percentage of time on average in five types of tasks than not-fatigued workers: repetitive processing or assembly (28.8% vs 5.6%), equipment operation (36.3% vs 3.4%), overhead work (19.5% vs 3.1%), maintenance (43.5% vs 5.2%), and material handling or lifting (35.9% vs 5.3%). Physically demanding work could increase the risk of fatigue and discomfort in body parts in both manufacturing (Vandergrift et al., 2012) and construction workplaces (Abdelhamid and Everett, 2002).

The descriptive statistics in Sec 2.3.1 and bivariate results above were also in accord with the three top causes (lack of sleep, work stress and shift schedule) reported in Sec 2.3.3. First, 65.2% of workers reported sleeping less than 7 hours (with 62.1% respondents sleeping 6 or fewer hours), and 86.7% of respondents worked more than 40 hours during a typical work week (with 25% of respondents working 55 hours or longer). These two items show the consistency with lack of sleep. Thus, the overall trends of short sleep duration and long work hours among manufacturing workers appear to be important. Second, work demands are one of the most common sources of work stress, and high physical workload has been related to both increased sleep problems and fatigue (Åkerstedt et al., 2002; Hancock and Desmond, 2001). Our bivariate analysis indicates that fatigued workers spent more time in the five work tasks supports that work stress as the second highest fatigue root cause. The fixed shift work was positively associated with fatigue when compared with rotating shifts, which could imply the two components of shift schedule, duration of shift and working times, could be dominant risk factors related with fatigue among manufacturing workers.

2.3.4 Overview of Individual Coping Measures

Survey results provide some insights on individual coping measures for fatigued respondents. From Figure 2.3, the bar chart shows the top three adopted recovery methods: drink caffeinated drinks (51.5%), stretch body or do exercises (36.9%), and chat with coworkers (30.8%). We suspect that these individual recovery strategies may have to do with the fact that they are not time-consuming, can be done in station, and can be repeated multiple times during the day with minimal disruption to the production schedule. Note that these recovery strategies potentially correspond to fatigue modes; for example, localized (e.g., stretching) vs whole-body (e.g., drinking, eating and talking to coworkers).

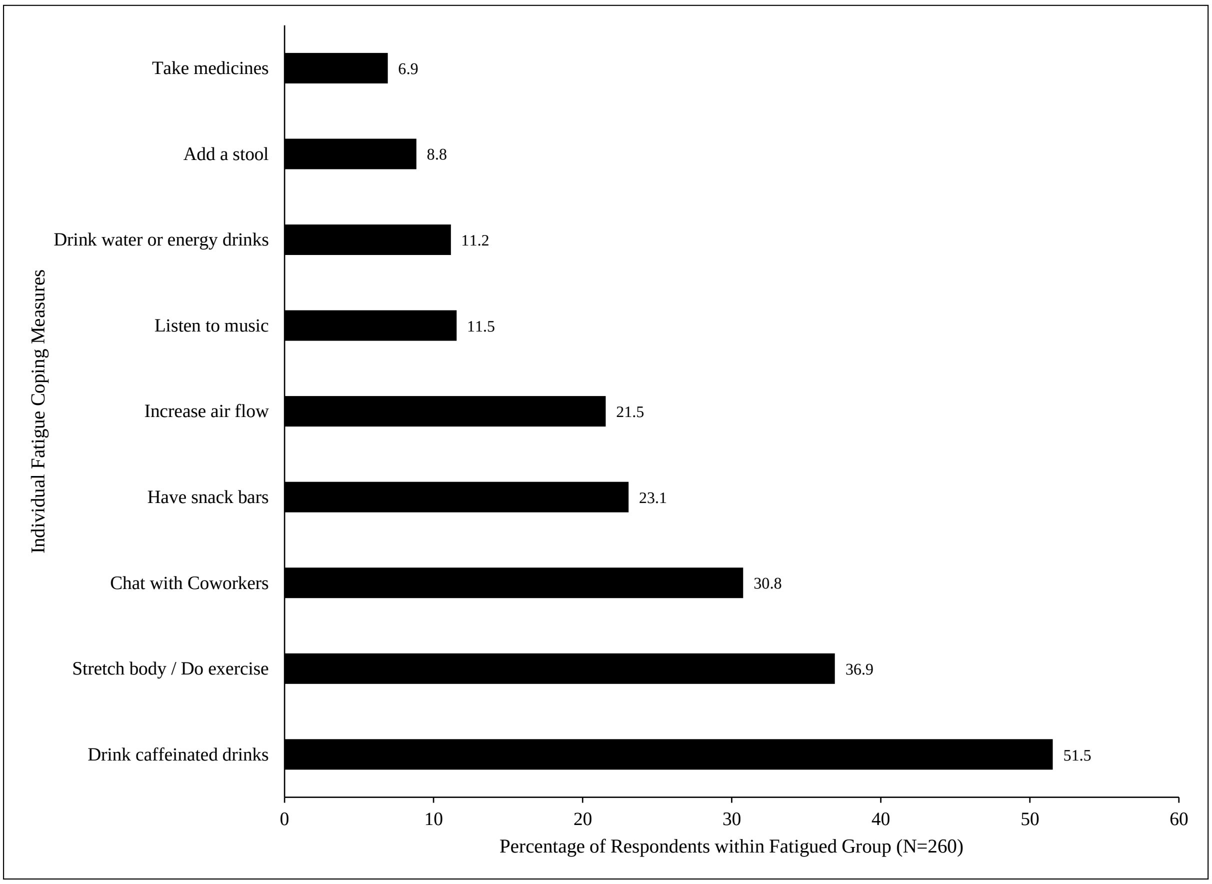

Figure 2.3: Percentage of Respondents Selecting a Recovery

The Market Basket Analysis for capturing the frequent combinations of individual coping measures is summarized in Table 2.6. Similar to Section 2.3.3, we only include the results where the support, confidence, and lift are greater than 15%, 50%, and 1, respectively. 20% of fatigued workers tend to both chat with coworkers and drink caffeinated drinks as coping mechanisms to combat fatigue (Table 2.6). The lift indicates that there is a 7% increase in probability of drinking caffeinated beverages (compared to selection at random) when chatting with co-workers is selected. Similar observations can be made for the relationship between having snack bars and drinking caffeinated beverages. In general, the relationship between drinking caffeinated beverages and the two coping mechanisms is logical, and seems to indicate that our respondents were consistent when responding to this question.

Table 2.6: Market Basket Analysis for Fatigue Root Causes ($n_f = 260$)

Set / Frequent Bucket	**Support (%)**	**Confidence (%)**	**Lift**
Chat with coworkers → Drink caffeinated drinks	20.9	61.3	1.07
Have snack bars → Drink caffeinated drinks	16.2	62.3	1.09

There were only 48 workers who indicated that their companies had methods for measuring/reporting fatigue. These methods included: (a) ongoing training to detect signs of fatigue in themselves or their coworkers, (b) encouraging reporting "issues" to supervisors, medical staff or going to first aid, (c) behavioral safety programs that had a component that indirectly relates to fatigue management, and (d) availability of health/fitness programs and/or stress management classes for employees. From these results, it seems that the state of fatigue management in manufacturing workplaces, as known or perceived by the workers themselves, lags the standards in the mining and transportation industries (Cavuoto and Megahed, 2016).

2.4 Conclusion

This study presents the results of a survey designed to address the prevalence of fatigue among U.S. manufacturing workers, the factors driving this fatigue and individual fatigue coping measures.

2.4.1 Limitations

The cross-sectional nature of the survey design limits the ability to discern the direction of observed associations. Causal relationships cannot be established. Moreover, though the completion rate of this survey (55.9%) was reasonable, a number of subjects stopped prior to completion. This may be due to unfamiliarity with the format of the online questions or the overall length of the survey. Subsequent research should include a longitudinal study or experiment and real-time monitoring of workplaces as an objective fatigue measurement that better assesses operation and real-world performance. Such monitoring should also include objectively assessing sleep duration and quality. In addition, follow-ups with manufacturing safety managers can be conducted for evaluating and enriching the existing fatigue intervention methods.

2.4.2 Strengths and Future Directions

The reader should note that the motivation and scope of this survey are different from other surveys, questionnaires, and scales that are found in the fatigue literature. First, the majority of the scales were originally developed for specific diseases though some were later expanded to healthy subjects (Krupp et al., 1989; Monk, 1989; Wood et al., 1990; Lee et al., 1991; Schwartz et al., 1993; Belza et al., 1993; Vercoulen et al., 1994; Smets et al., 1995; Fisk et al., 1994; Hann et al., 1998; Stein et al., 1998; Mendoza et al., 1999; Åhsberg, 2000; Winwood et al., 2005). The use of fatigue scales in medical practice allows for a large number of questions for each fatigue-related construct since: (a) the completion of the scale is attended by the administrator, and (b) the patient will directly benefit from the shared knowledge. However, our survey was designed for unattended completion and is anonymized. Thus, based on survey delivery and the feedback of several practitioners experienced with survey administration, we chose to limit the number of questions for each construct. Second, the time frame for the questions varied from "how are you feeling right now" to "over the past month." We chose the past week since: (a) it was a common measure for the average fatigue level, and (b) It is hypothesized that participants are more likely to have a better recollection of their fatigue level over the past week when compared to a longer time period (Broderick et al., 2008). Third, there is no single, agreed upon standard scaling used in the literature with the use of the visual analogue scale (VAS) and different variations of the Likert scale. In our survey, we chose to incorporate the VAS for the following reasons: (a) it can be modeled using a parametric approach (Svensson, 2001; McCormack et al., 1988; Svensson et al., 2001) and the responses can be normally distributed (Wolfe, 2004); (b) VAS scales are more sensitive than those with graduation since respondents can rate their subjective score when they perceive it falls between categories of a gradual scale (see e.g., Scott and Huskisson (1976); (c) VAS provides reliable measurements of subjective fatigue ratings (Hasson and Arnetz, 2005; Brunier and Graydon, 1996; Lee et al., 1991; Krupp et al., 1989); and (d) there is no recall bias when VAS measures are used to capture fatigue and pain, without the use of a log, over a one-week-period (Broderick et al., 2008).

Overall, the results of the survey helped identify a high (57.9%) weekly prevalence of reported fatigue among surveyed manufacturing workers. The top three frequently affected body regions where workers feel fatigued include ankles/feet, lower back, and eyes. Shoulders, head and neck are also rated high for fatigue frequency. Fatigue presence was associated with age, alcohol use, experience, hours of sleep, work hours per week, rotating shifts and frequency of performing work tasks. Work stress, lack of sleep, and shift schedule were selected as the top three root causes for fatigue among the 15 items given. Frequent combinations of the fatigue root causes were presented, one example of the combination set would be shift schedule, lack of energy, lack of sleep and poor environment.

Work designers and safety professionals can use the information provided by these results to design more effective fatigue management and mitigation strategies. Currently, a large proportion of fatigue measuring and reporting is reactive, which may not prevent injuries or errors. Understanding the causes, significant risk factors, and facilitated individual coping methods as well as implemented organizational reduction strategies for fatigue can lead to improved monitoring and recovery programs and therefore improve work performance.

Chapter 3

Interventions to mitigate fatigue induced by physical work: A systematic review of research quality and levels of evidence for intervention efficacy

3.1 Introduction

For the purpose of this review, physical fatigue is defined as being induced by a physical workload and manifesting as a lower level of strength and physical capacity (Lu et al., 2017; Gandevia, 2001; Vøllestad, 1997). Specifically, both central and peripheral origins of physical fatigue (Yung et al., 2017) are included as long as the fatigue is: (1) mainly induced by the physical workload, and (2) measured in a physical domain (e.g., specifying a fatigue measurement for overall / physical dimension or whole body / localized muscles). Central fatigue involves impairments in the muscle afferent system, and it is associated with spinal and supraspinal physiological phenomena (Behm, 2004). Note that mental or cognitive fatigue is distinguished from central fatigue in this review, and is not within the study scope, as central mechanisms might contribute to physical fatigue without changes in cognitive workload (Yung, 2016). Peripheral fatigue results from internal changes in muscles, including a lower level of contractile ability (Westerblad et al., 2010).

Commonly cited precursors of physical fatigue include: (a) heavy workloads, (b) awkward working postures, (c) prolonged working hours, (d) unstructured physical environment, textcolorredand/or (e) dynamic work conditions (Yung, 2016; Lu et al., 2017). Physical fatigue has been observed in several U.S. industries: (a) advanced manufacturing, where 57% of manufacturing workers have reported that they were fatigued over the past work week (Lu et al., 2017); (b) construction, where 49% of surveyed construction workers reported being “tired some days”, and 10% “tired most days or every day” (Zhang et al., 2015); and (c) fulfillment center order pickers, who pick 200-250 items per hour, walk approximately six miles per day, and have a 75% higher reported rate of musculoskeletal disorders (MSD) than the average employee (Schneider et al., 2010); this is a booming area of employment that is associated with e-commerce. It is important to note that the high prevalence of workplace fatigue is not limited to the U.S. alone; it has also been reported in Canada, the European Union and Japan (Yung, 2016; Loriol, 2017; Kajimoto, 2008).

Fatigue is a precursor to several short-term and long-term adverse health outcomes, which is supported by several papers analyzing the *Maastricht cohort study of fatigue at work*. For example, Janssen et al. (2003) showed that fatigue is related to both short-term and long-term sickness-related absenteeism. Moreover, Van Amelsvoort et al. (2002) showed that fatigue was a strong precursor of future disability pension. Other workplace studies have shown significant associations between physical fatigue and: (a) decreased physical and cognitive function (Zhang et al., 2015); (b) reduced in short-term work capacity (MacIntosh et al., 2004); (c) reduced leisure-time physical activity (Bláfoss et al., 2018); (d) diminished sensory motor coordination (GAGE, 1974); (e) an increased likelihood of occupational deafness (Larsen, 1953); (f) reduced work performance (Pasupathy and Barker, 2012; Barker and Nussbaum, 2011a); and (g) increased health-related complaints (Sluiter et al., 2003). The reader should note that these adverse health-outcomes also lead to a substantial cost to both employers and healthcare systems (the aforementioned studies were conducted in Europe and North America). Ricci et al. (2007) estimated that these outcomes cost U.S. employers $136 billion annually.

Several interventions have been designed to reduce the injury risks and lost productivity associated with fatigue. However, as stated in the U.S. National Occupational Research Agenda (NORA):

> [The] adoption of these interventions by employers is slow. There is a need to conduct additional intervention research that demonstrates the effectiveness of workplace changes in improving musculoskeletal health across a variety of outcomes, and to understand the facilitators and barriers to adoption of existing interventions by employers. Research to speed the adoption of effective interventions has the potential to dramatically reduce the frequency and severity of MSDs in the workplace. (National Occupational Research Agenda for Musculoskeletal Health, 2018, p. 11)

A first step towards meeting this NORA objective is to survey and assess the existing literature for workplace interventions that target physical fatigue. There are no published reviews that examine the efficacy of physical fatigue interventions in workplace settings. We did not review mental or sleep-related fatigue interventions since they have been examined in domain-specific reviews for the transportation (Rosekind et al., 1996; Caldwell, 2001) and nursing (Tiesinga et al., 1999; Steege et al., 2017) industries.

The overarching objective of this paper is to bring into better focus the literature on designing, developing and/or implementing interventions that reduce fatigue development and/or improve fatigue recovery. We performed a standard systematic review of the workplace fatigue intervention literature, focusing on articles that utilized randomized controlled trials (RCTs) or controlled clinical trials (CCTs). The following three main research questions are examined in this review:

(1) What are the characteristics of current workplace physical fatigue intervention studies?
(2) What is the methodological quality of each intervention study?
(3) What is the strength of evidence for each intervention?

From the systematic review, we hope to (i) present practitioners with insight into the effectiveness of interventions examined in the literature, and (ii) highlight gaps that require further study.

The remainder of this paper is organized as follows. Section 3.2 presents the methodology used for this systematic review. In Section 3.3, we divide the results from our systematic review into: (a) a summary of study characteristics; (b) an evaluation of the methodological quality of each study; and (c) an examination of the evidence supporting the efficacy of each intervention (categorized by individual-based and workplace-based interventions). In Section 3.4, we discuss the implications of the findings from this study and highlight opportunities for future intervention investigations. Finally, we present our repository containing code, data, and detailed analyses in the *Supplementary Materials Section*.

3.2 Methods

3.2.1 Search Strategy

PubMed was used to identify workplace physical fatigue intervention studies. The search was performed on March 28th, 2019, was limited to articles written in English, and used terms to capture the overlap between three fields: (a) *interventions*, (b) *health symptoms*, and (c) *workplace*. We excluded articles with several nonphysical and/or nonworkplace terms in the title/abstract or in the title from two rounds of prior searches. Table 3.1 shows the exact terms and the wildcard form used in our initial search. The reader should note that the "OR" operator was used to separate within field terms, and the "AND" operator was used to capture the intersection between the three fields. The wildcard form of certain search words was used to expand the search with more relevant terminologies or spellings without needing to explicitly include all possible combinations separately (Billings, 2003). To compile the results, we used the PubMed interface to download the relevant bibliographic materials (titles, abstracts, authors, keywords, and references cited). The reader is referred to the *Supplementary Materials Section* for the complete set of bibliographic data. In addition, to reproduce our PubMed results, one should visit https://www.ncbi.nlm.nih.gov/pubmed/?term= (while limiting the language as English and the date range from 1970-1-1 to 2019-3-28 to mimic the search).

Table 3.1: Terms included in the search. Note terms within and between fields denote "OR" and "AND", respectively.

Field	**Terms**
Interventions	compar*, effect, interven*, countermeasure*, coping, cope*, treatment*, program*, reduc*, decrease*
Health symptoms	fatigu*
Workplace	work*, work-related, operation*, occupation*, manufactur*, construction, mining, nurs*
Exclusion in Title	sleep*, eye*, vocal, voice, auditory, chronic*, ill*, disease*, sclerosis, stroke, fibromyaglia, review, optimiz*, predict*, model*, associat*, alloy*, scale*, protocol
Exclusion in Title/Abstract	cancer, patient*, driver*, alarm, child*, compassion, athlete*, player*, pregnan*

3.2.2 Selection of Studies

For this systematic review, five inclusion criteria were chosen. First, the intervention study was based on a RCT or a CCT (i.e., a clinical trial including two or more conditions, adapted from the definitions set forth by the National Institutes of Health and the National Cancer Institute). Second, the interventions were related to occupational settings (whether it was a field-based experiment that involved samples from true working population, or a laboratory study that mimicked occupational tasks/work and involved asymptomatic participants). Third, the interventions attempted to address physical fatigue with measurement outcomes (i.e., at least one outcome measuring physical work induced fatigue, either stating an overall or physical dimension, and targeting either the whole body or a localized region). Many manuscripts lack specificity with regards to the fatigue components and outcomes evaluated, leading to difficulty in identifying the type of fatigue assessed. Thus only those with physical fatigue outcome measures, as described in Section 2.3 below, were included. Visual, auditory and vocal fatigue were excluded since more specific mechanisms are involved beyond muscle fatigue. Fourth, the study was published in a journal (we excluded conference proceedings and book chapters since their peer review process is often not detailed). Fifth, the article was written in English (some of the search results included papers whose abstract was written in English while the full text was not).

The implementation of these criteria was performed through a sequential procedure conducted by a team of three reviewers (two faculty members and one PhD student all with training in occupational safety and ergonomics). The sequential procedure involved first examining the title of the paper, then the abstract (for papers that were deemed to be potentially relevant based on their title), and then the full-text (for papers potentially relevant based on their abstracts). At each stage, the number of documents was divided among the three reviewers such that each document was analyzed by two reviewers who had to agree on whether a study should enter the next stage of screening. In cases of disagreement between reviewers, the third reviewer was consulted to resolve any differences and reach a consensus. An overview of the procedure and the resulting number of papers are presented in Figure 3.1.

3.2.3 Outcome Measures

Physical fatigue can be measured either objectively or subjectively. Objective approaches include: (a) electromyography (EMG; e.g., using median frequency, normalized root mean square, mean power spectrum from the signals), (b) fatigue markers in blood (e.g., creatine kinase (CK), lactate dehydrogenase (LDH)), (c) strength capability (e.g., maximum voluntary

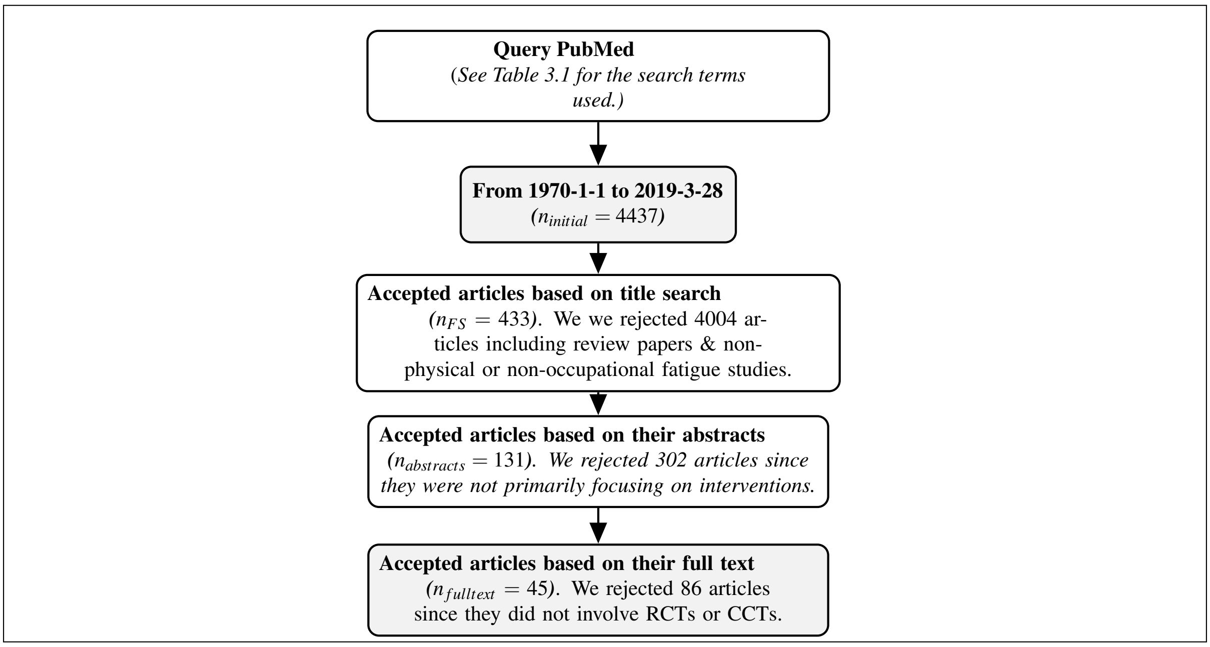

Figure 3.1: An overview of the sequential procedure for selecting relevant intervention papers. An Excel file documenting the results from each stage is available at: https://github.com/fmegahed/fatigue-interventions.

isometric contractions (MVCs)), or (d) through an index of physiological strain/metabolic rate (e.g., heart rate or postural sway). Typical subjective measures consist of self-reported fatigue or discomfort and evaluation surveys (e.g. Borg CR10, SOFI, VAS, FSI, FAS, MAF, CIS20-R, Likert-scale of severity). The reader is referred to Hjollund et al. (2007) and Whitehead (2009) for more details on these subjective measures.

The physical fatigue measures used by the authors of the included studies were the primary outcomes of interest. We did not define a standard set of fatigue outcomes of interest or exclude results based on the outcome measures used as we worked under the assumption that the authors justified and/or discussed the accuracy, sensitivity and feasibility of the applied measurement methods to be appropriate for their experiments. However, we do discuss the appropriateness and potential limitations of the chosen outcomes in the Discussion section below. Due to the variety of work tasks tested and the lack of standardized and universal fatigue measures, each measure has limitations. For example, EMG can reflect either central or peripheral fatigue when an increase in root-mean-square amplitude is concomitant with a decrease in either mean or median power frequency (Cifrek et al., 2009), however, interpretation is affected for dynamic tasks due to changing blood flow, a potentially non-stationary signal for frequency-domain transformation, and muscle-electrode movement (Cifrek et al., 2009). Fatigue markers in the blood can also be accurate, but may not be feasible in occupational settings. Other direct fatigue measures, such as change in MVCs or isometric lifting force (ILF) (Vøllestad, 1997), may be influenced by subject motivation (Yung and Wells, 2017; Kankaanpää et al., 1997).

These physical fatigue outcomes can be compared within and/or between interventions using one or more of the following forms: (a) cross-sectional values following the intervention; (b) rates of change during work, recovery, and/or postrecovery periods; or (c) mean difference, percent difference, effect size, or percentage of improvement of participants from pre- to postintervention or between interventions. Whenever the baseline data of each intervention group is given, and significance tests within or between groups were conducted, mean percent changes were calculated based on the paper results to derive effectiveness measures of effect size or mean percent difference.

3.2.4 Data Extraction

After selecting the papers to be included in the review, we extracted data from each paper to capture the study characteristics, examine the methodological quality, and grade the evidence supporting the quality of the interventions. The captured data included: (a) subject characteristics (i.e., sample size, age, and sex); (b) targeted type of tasks and industries; (c) body locations of fatigue (i.e., localized or whole body); (d) outcome measures used by the research team; (e) work duration tested for intervention exposure; (f) experimental setup (laboratory vs. field study); (g) descriptions of interventions deployed; (h) the design of the experiment (RCT vs. CCT); and (i) the effect of the interventions (percent difference, effect size, conclusions). These characteristics are important for examining the methodological quality, and grading the levels of evidence associated with each intervention.

3.2.5 Assessment of Methodological Quality

The methodological quality of all trials was evaluated using the PEDro scale, which was developed by Verhagen et al. (1998). The PEDro scale has been shown to have acceptably high interrater reliability (Moseley et al., 1999; Sherrington et al., 2000). There are eleven criteria in the PEDro scale, and their descriptions were referred by Maher et al. (2003) and Heine et al. (2015): (a) criterion 1 relates to the external validity (the generalizability or applicability) of the trial; (b) criteria 2-9 test the trial's internal validity; and (c) criteria 10-11 examine if the study has sufficient statistical information to make the reported results interpretable. All trials were rated by two raters with discrepancies in rating arbitrated by a third rater. The three raters were two professors and one PhD student who also participated in the previous step of literature screening. Studies that scored $\geq$ 6/11 were categorized as high quality studies and those scoring $<$ 6/11 were categorized as low quality studies (Maher, 2000).

3.2.6 Levels of Evidence

Summary descriptions on the efficacy of the interventions were based on a rating system described by Van Tudler and colleagues (Van Tulder et al., 1997). This system considers the consistency, quality and number of studies from RCTs. The results are considered to be consistent if $\geq 75\%$ of the studies reported the same conclusion of effect.

- Strong evidence: $\geq$ 2 high quality RCTs with consistent outcomes
- Moderate evidence: 1 high quality RCT and $\geq$ 1 low quality RCT(s) with consistent outcomes
- Limited evidence: 1 high quality RCT or $\geq$ 2 low quality RCTs with consistent outcomes
- Minimal evidence: 1 low quality RCT, no RCTs, or inconsistent outcomes

If the main studies were CCTs rather than RCTs, the level of evidence was downgraded by one level. This procedure is consistent with the hierarchy of evidence described by Paci et al. (2009) and Paci et al. (2011). For example, if there are two high quality CCTs within an intervention category, the level of evidence of that intervention will be moderate rather than strong. The specific grading for the level of evidence is summarized in Table 3.2. The level of evidence for each intervention category was based on the combined effects determined across muscle groups.

Table 3.2: Level of Evidence based on the main two papers within an intervention category

	High Quality RCT	Low Quality RCT	High Quality CCT	Low Quality CCT	No 2nd Paper
High Quality RCT	Strong	Moderate	Moderate	Limited	Limited
Low Quality RCT		Limited	Limited	Minimal	Minimal
High Quality CCT			Moderate	Limited	Minimal
Low Quality CCT				Minimal	Minimal

3.3 Results

3.3.1 Study Characteristics

Based on the discussion in Section 3.2.2 and the summary in Figure 3.1, our search terms resulted in a total of 4,437 unique studies. These studies represent a comprehensive search of relevant articles in PubMed and also cover all the studies that met the inclusion criteria and that were identified in our first and second searches. Upon applying our inclusion and exclusion criteria, 45 studies were identified as the most relevant studies to be included in this systematic review. An overview of these 45 studies, organized by the type of intervention used, is presented in Table 3.3. Among the 45 studies, 18 interventions were identified and each intervention was categorized as an individual-, or workplace-focused intervention or as multiple interventions, and whether the intervention changed the main work process was considered.

In Table 3.3, there are several important findings that should be highlighted. First, most of the intervention studies (30 out of 45) were published since 2010. Eleven of the fifteen studies that were published prior to 2010 were individual-focused interventions that involved the use of mats/shoe insoles (5 studies), assistive devices (3 studies), posture variation (1 study), exercise (1 study), or a combination of mat/shoe insoles and posture variation (1 study). The remaining four work-focused interventions involved tool redesign, rest breaks, participatory ergonomics, and a combination of changing work pace, rest breaks, and changing work duration. After 2010, one can see the role of technology in recent intervention studies and the customization of interventions towards for a variety of work tasks.

Table 3.3: An overview of the characteristics of the included studies. Note we use n, I, and C to denote sample size, intervention group and control group, respectively. Additionally, M is used to denote males and F is used for females.

Intervention Category	**Reference**	**Population and Sample Size**	**Mean Age (Std Dev.)**	**Work Type**	**Fatigue Location**	**Work Duration**	**Outcome Measures**	**Field/ Lab**
(A) Individual-focused interventions								
Assistive device	Majkowski et al. (1998) | CCT (crossover) examines the effects of back belts on fatigue of lumbar paraspinal muscles	Healthy duty military population $n_{total} = 24$ $(n_M = 13)$ $n_{IC1} = 20$ & $n_{IC2} = 4$	$IC1 = 32$ (6.5) & $IC2 = 30$ (3.6)	Dynamic lifting	Lumbar	20-min	Isometric lifting force, MPF of EMG	Lab
	Iwakiri et al. (2008) | RCT (crossover) evaluates whether a standing aid can alleviate fatigue in the kitchen of nursing home	Healthy, female cooks with no back pain or disorders $n_{total} = 12$ $(n_F = 12)$	$IC = 52$ (7.6)	Forward-bent posture	Overall	9-hr	VAS	Field
	Lotz et al. (2009) | RCT (crossover) determines if a personal lift assist device can reduce general and local back muscle fatigue during a cyclic lifting task	Healthy, male volunteers with no back pain history $n_{total} = 10$ $(n_M = 10)$	$IC = 22$ (3.8)	Repetitive lifting	Lumbar	45-min	RMS & MDF of EMG, heart rate, Borg RPE 6-20, back extensor strength & duration	Lab
	Rashedi et al. (2014) | CCT (crossover) evaluates if the wearable assistive device effects on localized fatigue for overhead work	Convenience sample from the university and local community $n_{total} = 12$ $(n_M = 12)$	$IC = 27$ (2.6)	Overhead	Upper extremities, Lumbar	10-min	Borg CR10, nRMS of EMG	Lab
	Miura et al. (2018a) | CCT (crossover) investigates the hybrid assisted limb for Care Support robot can reduce lumbar fatigue	Healthy, injury-free men volunteers who had experience with snow shoveling $n_{total} = 9$ $(n_M = 9)$	$IC = 31$ [26,44]	Repetitive snow-shoveling	Lumbar	Until fatigued, within 366-sec	VAS	Field
	Miura et al. (2018b) | CCT (crossover) investigates the hybrid assisted limb for Care Support robot can reduce lumbar fatigue	Healthy, injury-free men volunteers $n_{total} = 18$ $(n_M = 11)$	$IC = 31$ (6.1)	Repetitive lifting	Lumbar	Until fatigued, within 332-sec	VAS	Lab
	Bazazan et al. (2019) | CCT examines effects of posture correction-based intervention (with a biofeedback device) on the occurrence of fatigue among control room operators in petrochemical plant	Full-time control room operators $n_{total} = 193$ $(n_M = 203)$ $n_I = 96$ $n_C = 97$	$I = 32.8$ (5.3) $C = 33.1(4.0)$	Prolonged sitting	Overall	12-week, twice per day, 30-min	MFI-20	Field
Posture variation	Meyer and Radwin (2007) | RCT (crossover) examines stooped and prone postures using simulated agricultural harvesting task	Healthy, non-smoking male students free from back pain or treatment for at least 6 months $n_{total} = 14$ $n_M = 14$	$IC = 23$ (37)	Repetitive lowering	Upper extremities, Lumbar, Lower extremities	30-min	RMS & MPF of EMG	Lab

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Table3.3 – *Continued from previous page*

Intervention Category	**Reference**	**Population and Sample Size**	**Mean Age (Std Dev.)**	**Work Type**	**Fatigue Location**	**Work Duration**	**Outcome Measures**	**Field/ Lab**
	Thorp et al. (2014) | RCT (crossover) study examines intermittent standing on subjective fatigue for overweight/obese office workers	Overweight/obese office workers $n_{total} = 23$ ($n_M = 17$)	$IC = 48.2$ (7.9)	Prolonged sitting	Overall	5-day, 8-hr per day	CIS-20R, MAF-GFI	Lab
	Tanoue et al. (2016) | RCT (crossover) study examines dynamic sitting balance chair on reducing lumbar fatigue for simulated office work	Healthy students $n_{total} = 17$ ($n_M = 10$)	$IC = 21.9$ (2.7)	Prolonged sitting	Lumbar	30-min	VAS	Lab
	Son et al. (2018) | RCT (crossover) examines footrest heights to reduce fatigue for prolonged standing	Subjects with non-specific lower back pain $n_{total} = 13$ ($n_M = 13$)	$IC = 24.2$ (1.9)	Prolonged standing	Lumbar	2-hr	MDF & MAR of EMG	Lab
	Lee et al. (2018) | RCT (crossover) evaluates fatigue with and without a footrest during prolonged standing	Convenience sample through personal and professional networks $n_{total} = 20$ ($n_M = 7$)	$IC_M = 26.1$ (11.6) $IC_F = 29.2$ (9.4)	Prolonged standing	Lumbar	2-hr	MDF & Amplitude of EMG	Lab
	Bao and Lin (2018) | RCT (crossover) investigates effects of four sit/stand schedules on muscle fatigue for office work	Healthy and asymptotic office workers $n_{total} = 12$ ($n_M = 8$)	$IC = 32.4$ (7.2)	Prolonged sitting	Upper extremities, Lumbar	8-hr workday	MDF of EMG	Field
	Baker et al. (2018) | RCT (crossover) investigates whether the use of movement (with a footrest) during prolonged standing affect fatigue	Volunteers recruited through personal and professional networks $n_{total} = 20$ ($n_M = 7$)	$IC = 28.3$ (9.9)	Prolonged standing	Lumbar, Lower extremities	2-hr	MDF & Amplitude of EMG	Lab
Mats/shoe insoles	Kim et al. (1994) | RCT (crossover) on the use of mats to relieve back and leg fatigue for prolonged standing	Student volunteers $n_{total} = 5$ ($n_F = 3$)	$IC = [21, 25]$	Prolonged standing	Lumbar, Lower extremities	2-hr	MDF of EMG	Lab
	Madeleine et al. (1997) | CCT (partial crossover) evaluates standing on hard and soft surfaces on fatigue in prolonged manual work	Healthy and unmedicated male volunteers $n_{total} = 13$ ($n_M = 13$) $n_I = 11$ $n_C = 10$	$I\&C = 23.3$ (0.5)	Prolonged standing	Lower extremities	2-hr	MPF & RMS of EMG, Moment, Duration of MVC	Lab
	Kelaher et al. (2000) | CCT (crossover) assesses the prefabricated semi-rigid orthotics on fatigue resistance	Asymptomatic subjects not worn arch support orthotics previously $n_{total} = 12$ ($n_M = 5$)	$IC = 25.8(8.4)$	Prolonged standing	Overall	18-week, 2-hr per week	A-P sway, lateral sway & total sway speeds, sway speed ratio	Lab
	Cham and Redfern (2001) | RCT (crossover) examines the influence of flooring on fatigue for prolonged standing	Healthy participants $n_{total} = 10$ ($n_M = 5$)	$IC = 27$ (6)	Prolonged standing	Overall, Lower extremities, Lumbar	4-hr	Borg CR10, MDF of EMG	Lab

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Table3.3 – *Continued from previous page*

Intervention Category	**Reference**	**Population and Sample Size**	**Mean Age (Std Dev.)**	**Work Type**	**Fatigue Location**	**Work Duration**	**Outcome Measures**	**Field/ Lab**
	King (2002) | RCT (crossover) on the use of floor mats and shoe in-soles to relieve standing fatigue for assembly line workers	Factory workers $n_{total} = 22$ ($n_F = 17$)	$IC = 52.1$	Prolonged standing	Overall, Lower extremities	7-day, 8-hr per day	Rating (1-5)	Field
Exercise	Hamberg-van Reenen et al. (2009) | RCT investigates a resistance-training program on muscle fatigue (most are office workers)	Convenience sample of healthy workers $n_{total} = 19$ $n_I = 9$ ($n_F = 6$) $n_C = 10$ ($n_F = 7$)	$I = 36.6$ (9.0) $C = 37.8$ (10.3)	Simulated assembly & lifting	Upper extremities, Lumbar	8-week, two 1-hr per week	MPF & Amplitude of EMG	Field
	de Vries et al. (2017) | RCT on the use of exercise to reduce fatigue among employees (most in education or healthcare sector)	Fatigued employees $n_{total} = 96$ ($n_M = 57$) $n_I = 49$ $n_C = 47$	$I = 44.2$ (11.9) $C = 46.29$ (9.3)	Variety	Overall	6-week, three 1-hr per week	FAS (10-50)	Field
Relaxation therapy	Keller et al. (2012) | RCT (partial crossover) assesses the efficacy of massage therapy in health care employees	Cardiac catheterization lab staff who wear lead aprons $n_{total} = 60$ ($n_M = 33$) $n_{I1C1} = 25$ $n_{I2} = 25$ $n_C = 10$	$I1C1 = 43.7$ (10.5) $I2 = 40.5$ (8.9) $C = 42.4(7.0)$	Repetitive activities, heavy load	Overall	5 & 10-week, 30-min per week	VAS	Field
	Rapolienė et al. (2016) | RCT investigates the influence of high-salinity geothermal mineral water bath on fatigue for highly stressful occupations	Seamen work over 5 years and fatigue level more than 2 $n_{total} = 180$ ($n_M = 180$) $n_{I1} = 65$ $n_{I2} = 50$ $n_C = 65$	$I1 = 47.5$ (10.6) $I2 = 47.6$ (10.7) $C = 46.2$ (9.3)	High stressful	Overall	2-week, 15-min for 5 times per week	MFI	Field
Garment Change	Chan et al. (2016) | RCT (crossover) investigates the effect of wearing compression garments on perceptual fatigue (e.g. construction & mining)	Healthy, physical active participants with manual-labor work experience $n_{total} = 10$ ($n_M = 10$)	$IC = 23$ (3)	Manual labor tasks	Overall	4-hr	BRUMS-fatigue	Lab
	Jensen et al. (2016) | RCT (crossover) determines cooling garment efficacy in improving time to functional fatigue in the medical community	Novice & experienced surgeons $n_{total} = 19$ $n_{novice} = 10$ ($n_F = 6$) $n_{experienced} = 9$ ($n_M = 9$)	$novice = 31.2$ (2.1) $experienced = 60.9$ (8.0)	Flexion-extension	Upper extremities	Until fatigued, within 6-min	Time to functional fatigue	Lab
Oral rehydration	Ishikawa et al. (2010) | RCT (crossover) on the use of oral rehydration to reduce fatigue in hot environment for aircraft ground handling	Workers engaged in loading cargo $n_{total} = 153$ ($n_M = 142$)	$IC = 25.6$ (6.4)	Outdoor, manual work	Overall	1-day	VAS	Field
Chemical supplements	Suh et al. (2012) | RCT on the use of intravenous vitamin C to reduce fatigue for office workers	Office workers or sales personnel $n_{total} = 141$ ($n_M = 59$) $n_I = 70$ $n_C = 71$	$I = 30.4$ (5.7) $C = 31.2$ (5.8)	Variety	Overall	2-hr	Rating (0-10)	Field

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Table3.3 – *Continued from previous page*

Intervention Category	**Reference**	**Population and Sample Size**	**Mean Age (Std Dev.)**	**Work Type**	**Fatigue Location**	**Work Duration**	**Outcome Measures**	**Field/ Lab**
Micro-current stimulation	Kang et al. (2015) | RCT measures impact of low-frequency electrical stimulation on fatigue recovery for repetitive lifting and lowering	Right-hand dominant, healthy volunteer $n_{total} = 32$ $(n_M = 32)$ $n_{I1} = 12$ $n_{I2} = 10$ $n_C = 10$	$I1 = 21.8$ (1.8) $I2 = 22.4$ (1.5) $C = 21.5$ (1.8)	Repeated lifting & lowering	Lumbar	15-min	MDF of EMG, muscle tones, CK & LDH	Lab
(B) Workplace-focused interventions								
Task variation	Evstigneeva et al. (2012) | CCT (crossover) on the use of concurrent cognitive task to slow fatigue in motor work	Right-handed students $n_{total} = 17$ $(n_F = 11)$	$IC = 24$ (1.4)	Handgrip test	Overall	12-min	Borg CR10	Lab
	Mathiassen et al. (2014) | CCT (crossover) on the use of cognitive activities during breaks to recover from fatigue in repetitive manual work	Healthy subjects $n_{total} = 18$ $(n_M = 18)$	$IC = 24.2$ (4.3)	Repetitive assembly	Upper extremities	97-min	Borg CR10, SOFI, RMS & MPF of EMG	Lab
	Luger et al. (2015) | CCT (crossover) examines effects of task variation on shoulder fatigue for simulated, repetitive, low-intensity work	Healthy, right-handed subjects $n_{total} = 14$ $(n_M = 7)$	$IC = 23.8$ (2.8)	Repetitive assembly	Upper extremities	1-hr	MDF & ARV of EMG	Lab
	Luger et al. (2016) | CCT (crossover) on the use of rotation between dynamic and static work to relieve fatigue for manual material handling work	Healthy, right-handed subjects $n_{total} = 10$ $(n_M = 5)$	$IC = 26.0$ (3.1)	Dynamic lifting, pick & place	Upper extremities	1-hr	Borg CR10, SOFI, ARV & MAD of EMG	Lab
Tools redesign	Rempel et al. (2009) | RCT (crossover) investigates an inverted drill press and a foot lever design on regional body fatigue in the construction sector	Full-time construction $n_{total} = 14$ $(n_M = 12)$	$IC = 35$ [24-53]	Overhead drilling	Upper extremities, Lumbar, Lower extremities	1-2 hrs	Rating (0-5)	Field
	Kim et al. (2014) | RCT tests the effect of table height on shoulder muscle fatigue for physical therapists	Healthy, male adults $n_{total} = 63$ $(n_M = 63)$ $n_{I1} = 31$ $n_{I2} = 31$ $n_C = 31$	$I1\&I2\&C = 22.1$ (2.8)	Therapeutic ultra-sounds work, repetitive low-load	Upper extremities	5-min	MDF of EMG	Lab
	Allahyari et al. (2016) | CCT (crossover) investigates two workstations on fatigue in hand carpet weaving	Right-handed female carpet weavers $n_{total} = 12$ $(n_F = 12)$	$IC = 32.5$ (6.8)	Static, awkward posture	Upper extremities	3-hr	Borg CR10, MDF & RMS of EMG	Lab
Rest break	Crenshaw et al. (2006) | CCT (crossover) examines active versus passive pauses on fatigue rating in computer mouse task	Right-handed female university students $n_{total} = 15$ $(n_F = 15)$	$IC = [19, 24]$	Computer mouse	Upper extremities	60-min	MDF & amplitude of EMG, Borg CR10	Lab
	Mailey et al. (2017) | RCT on the use of short-frequent/long-planned breaks to reduce fatigue for sedentary female employees	Office workers $n_{total} = 36$ $(n_F = 36)$ $n_{I1} = 20$ $n_{I2} = 16$	$I1\&I2 = 39$ (7.9)	Prolonged sitting	Overall	8-week	FSI	Field

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Table3.3 – *Continued from previous page*

Intervention Category	**Reference**	**Population and Sample Size**	**Mean Age (Std Dev.)**	**Work Type**	**Fatigue Location**	**Work Duration**	**Outcome Measures**	**Field/ Lab**
Participatory Ergonomics	Brandt et al. (2018) | RCT investigates whether a participatory ergonomics intervention with technical measurements can decrease general fatigue in the construction industry	Full-time construction workers $n_{total} = 80$ $n_M = 80$ $n_I = 32$ $n_C = 48$	I = 34.2 (12.5) C = 41.2 (12.5)	Heavy-load	Overall	3 & 6 months	Rating (1-5)	Field
	Haukka et al. (2008) | A cluster RCT examines a participatory ergonomics intervention on local fatigue after kitchen work	Kitchen workers $n_{total} = 504$ $n_I = 263$ $(n_F = 252)$ $n_C = 241$ $(n_F = 236)$	I = 46, [19,63] C = 47, [19,62]	Physical demanding	Local	12 months	Rating (1-6)	Field
Change work pace	Bosch et al. (2011) | RCT (crossover) investigates the effect of work pace on fatigue during light assembly	Healthy, right-handed subjects $n_{total} = 8$ $(n_F = 8)$	IC = 20.5 (1.8)	Repetitive assembly	Upper extremities	2-hr	Borg CR10, MVF, Amplitude & MPF of EMG	Lab
(C) Multiple interventions								
Mats/shoe-insoles & Posture variation	Hansen et al. (1998) | CCT (crossover) investigates the significance of mat and shoe softness during prolonged work in an upright position	Healthy, female volunteers $n_{total} = 8$ $(n_F = 8)$	$IC = 24$ [21,29]	Sitting /standing, prolonged standing	Lumbar	2-hr	RMS & MPF of EMG	Lab
	Garcia et al. (2016) | RCT (crossover) evaluates a hard floor, floor mat, or slow-pace walking for standing work on muscle twitch force	Healthy, young adults $n_{total} = 18$ $(n_M = 10)$	$IC = 25$ (4)	Prolonged standing	Lower extremities	320-min	Amplitude & duration of MTF	Lab
Change work pace & Rest break & Change work duration	Mathiassen and Winkel (1996) | CCT (crossover) compares reduced work pace, increased break and shortened work on limiting acute fatigue	Asymptomatic subjects that had no previous assembly work experience $n_{total} = 8$ $n_F = 8$	$IC = 27$ [22,32]	light assembly	Upper extremities	2-6 hrs	Amplitude & MDF of EMG, Borg CR10	Lab
Posture variation & Rest break	Garcia et al. (2018) | RCT (crossover) assesses the change in fatigue with work-rest cycles and/or rest-break types	Healthy individuals $n_{total} = 30$ $(n_M = 15)$	$IC = 30$ (12)	Prolonged standing	Lower extremities	5-hr	Amplitude & duration of MTF	Lab
Tools redesign & Rest break	Callegari et al. (2018) | RCT (crossover) investigates whether the use of hand rest or the wrist support change muscle fatigue	Right-handed female volunteers who used computer less than 4 hr/week $n_{total} = 30$ $(n_F = 30)$	$IC = [20, 30]$	Prolonged typing	Upper extremities	4-hr	RMS & MDF of EMG	Lab

VAS: Visual Analog Scale, CIS: Checklist Individual Strength, FAS: Fatigue Assessment Scale, MAF: Multidimensional Assessment of Fatigue, FSI: Fatigue Symptom Inventory, MD/PF: Median/Mean Power Frequency, (n)RMS: (normalized) Root Mean Squared, MTF: Muscle Twitch Force, MAR: Muscle Activity Ratio, ARV: Average Rectified Value, SD: Standard Deviation, CK: Creatine Kinase Lactate, LDH: Lactate Dehydrogenase, RPE: Rate of Perceived Exertion, BURMS: Brunel Mood State Questionnaire, GFI: Global Fatigue Index, MTM: Methods-time measurement, MAD: Median Absolute Deviation, MVC/F: Maximum Voluntary Contraction/Force, SOFI: Swedish Occupational Fatigue Inventory.

The second observation combines information captured in the "Reference" and "Population and Sample Size" columns. Thirty of the 45 studies were RCTs, and the remaining were

CCTs. It should also be noted that 33 of the 45 studies included crossover designs and two studies used partial crossover designs. Among the 30 RCTs, 20 were crossover studies with random allocation of experiment orders.

The third observation pertains to the participants recruited in these studies. From the 45 studies, 24 studies included subjects of both sexes, 13 studies included only male participants, and the remaining eight studies included only female participants. The average age distribution of the studies was as follows: 25 studies had an average age of participants in the 20s, 12 studies had an average age of participants in the 30s, six studies in the 40s, and two studies in the 50 s. From these participants' information, one could see that most of the studies used a convenience sample of college-aged students, which does not typically correspond to the demographics seen in the workplace. This sampling method is a potentially limiting factor in the published literature.

The fourth observation pertains to the targeted types of work. Prolonged posture, repeated lifting or lowering, and repetitive assembly (pick-and-place belong to this category) tasks were the top 3 mentioned work tasks among the selected literature, respectively. Other studies covered overhead work, computer work, simulated work (flexion-extensor, handgrip test) and outdoor tasks. Heavy-load, repetitive low-load and a variety of tasks were also common in the selected studies. Corresponding to these work tasks, the locations of fatigue included the upper extremities (shoulders, arms, wrists), the lumbar region (erector spinae, lumbar paraspinal muscles), the lower extremities (legs, feet, ankles) and overall fatigue.

The fifth observation relates to the work duration for intervention exposure. Among the 45 intervention studies, the length of work in only nine studies was shorter than 1 hour, and all other studies ranged from 1 hour to a year depending on the specific work tasks and intervention categories.

Sixth, the choice of outcome measures used by the experimenters was almost uniformly distributed. Eighteen studies used only objective measures, and 18 studies elected to use only subjective measures. The remaining nine studies utilized both objective and subjective fatigue measures in their experiment. The most commonly used outcome measures were EMG and subjective ratings of fatigue.

The seventh and final observation relates to the work environment where the experiment was conducted. In our review, 30 studies were performed in a laboratory setting, and the remaining 15 were performed in the field. Note that field studies tended to have larger sample sizes.

3.3.2 Methodological Quality

Based on the discussion in Section 3.2.5, any study scoring $\geq \frac{6}{11}$ is considered high quality. Thirty studies scored $\geq \frac{6}{11}$ on the PEDro scale, including the study by Suh et al. (2012), which obtained a perfect score. Table 3.4 presents the details underlying the numeric quality score assigned to each study.

As shown in Table 3.4, all the studies fulfilled Criteria 1 and 10 on the PEDro scale. Criterion 1 indicates that the "eligibility criteria were specified" for a given study. Criterion 10 examines whether "the results of between-group statistical comparisons are reported for at least one key outcome". For Criterion 2, there were 15 studies that did not satisfy the random allocation requirement. Those studies either did not specify randomness in assigning individuals to groups or in setting the experimental order (e.g., presetting orders, using balanced crossover design, or quasirandomization by using the last digit of a participant's social security number). Forty studies failed the *concealed allocation* associated with Criterion 3. For Criterion 4, 30 studies reported the similarity of fatigue outcome at baseline between the different groups or presented data that would support this conclusion. Criteria 5-7 assess the blinding of subjects, therapists, and assessors, respectively. These criteria were not met by most studies due to the nature of the experiments. The reader should note we only considered blinding to be true if it was explicitly mentioned in the study description. Thirty-seven papers reported that $\geq 85\%$ of the subjects participated in the follow-up fatigue measurement. Those 37 papers met the lower limit set by Criterion 8. For Criterion 11, all the studies conducted between-group comparisons for at least one fatigue outcome; however, seven studies failed to provide data for the exact point estimates or measures of variability for at least one key fatigue outcome.

Table 3.4: Methodological quality scores assigned to each study by our reviewers based on the PEDro score

Intervention Category	**Reference**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Total**	**Quality (>=6)**
(A) Individual-focused interventions														
Assistive device	Majkowski et al. (1998)	1	0	0	1	0	0	0	0	1	1	0	4	low
	Iwakiri et al. (2008)	1	1	0	0	0	0	0	1	1	1	1	5	low
	Lotz et al. (2009)	1	1	0	1	0	0	0	1	1	1	1	7	high
	Rashedi et al. (2014)	1	0	0	1	0	0	0	1	1	1	0	5	low
	Miura et al. (2018a)	1	0	0	0	0	0	0	1	1	1	1	5	low
	Miura et al. (2018b)	1	0	0	0	0	0	0	1	1	1	1	5	low
	Bazazan et al. (2019)	1	0	0	1	0	0	0	1	1	1	1	6	high
Posture variation	Meyer and Radwin (2007)	1	1	0	1	0	0	0	1	0	1	1	6	high
	Thorp et al. (2014)	1	1	0	1	0	0	1	1	1	1	1	8	high
	Tanoue et al. (2016)	1	1	0	1	0	0	0	1	1	1	1	7	high
	Son et al. (2018)	1	1	0	1	0	0	0	1	1	1	1	7	high
	Lee et al. (2018)	1	1	0	1	0	0	0	1	1	1	1	7	high
	Bao and Lin (2018)	1	1	0	1	0	0	0	1	1	1	1	7	high
	Baker et al. (2018)	1	1	0	1	0	0	0	1	0	1	1	6	high
Mats/shoe insoles	Kim et al. (1994)	1	1	0	0	0	0	0	1	1	1	0	5	low
	Madeleine et al. (1997)	1	0	0	1	0	0	0	1	1	1	1	7	high
	Kelaher et al. (2000)	1	0	0	1	0	0	0	1	0	1	1	5	low
	Cham and Redfern (2001)	1	1	0	0	0	0	0	1	1	1	0	5	low
	King (2002)	1	1	0	0	0	0	0	0	0	1	1	4	low
Exercise	Hamberg-van Reenen et al. (2009)	1	1	1	1	0	0	0	1	0	1	1	7	high
	de Vries et al. (2017)	1	1	1	1	0	0	0	0	1	1	1	7	high
Relaxation therapy	Keller et al. (2012)	1	1	0	1	0	0	0	1	1	1	1	7	high
	Rapolienė et al. (2016)	1	1	0	1	0	0	0	0	0	1	1	5	low
Garment change	Chan et al. (2016)	1	1	0	1	0	0	0	1	1	1	1	7	high
	Jensen et al. (2016)	1	1	0	0	0	0	0	1	1	1	0	5	low
Oral rehydration	Ishikawa et al. (2010)	1	1	0	0	0	0	0	1	1	1	1	6	high
Chemical supplements	Suh et al. (2012)	1	1	1	1	1	1	1	1	1	1	1	11	high
Micro-current stimulation	Kang et al. (2015)	1	1	0	1	0	0	0	1	1	1	1	7	high
(B) Workplace-focused interventions														
Task variation	Evstigneeva et al. (2012)	1	0	0	1	0	0	0	1	1	1	1	6	high
	Mathiassen et al. (2014)	1	0	0	1	0	0	0	1	1	1	1	6	high
	Luger et al. (2015)	1	0	0	1	0	0	0	1	1	1	1	6	high
	Luger et al. (2016)	1	0	0	1	0	0	0	1	1	1	1	6	high
Tools redesign	Rempel et al. (2009)	1	1	0	0	0	0	0	1	1	1	1	6	high
	Kim et al. (2014)	1	1	0	0	0	0	0	1	1	1	1	6	high
	Allahyari et al. (2016)	1	0	0	1	0	0	0	1	1	1	1	6	high
Rest break	Crenshaw et al. (2006)	1	0	0	1	0	0	0	1	1	1	1	7	high
	Mailey et al. (2017)	1	1	0	1	0	0	0	0	1	1	1	6	high
Participatory ergonomics	Brandt et al. (2018)	1	1	1	1	0	0	1	0	1	1	1	8	high
	Haukka et al. (2008)	1	1	1	0	0	0	0	1	1	1	1	7	high
Change work pace	Bosch et al. (2011)	1	1	0	0	0	0	0	1	1	1	0	5	low
(C) Multiple interventions														
	Hansen et al. (1998)	1	0	0	1	0	0	0	1	1	1	0	5	low
	Garcia et al. (2016)	1	1	0	1	0	0	0	0	1	1	1	6	high
	Mathiassen and Winkel (1996)	1	0	0	0	0	0	0	1	1	1	1	5	low
	Garcia et al. (2018)	1	1	0	0	0	0	0	1	1	1	1	6	high
	Callegari et al. (2018)	1	1	0	0	0	0	0	0	0	1	1	4	low

3.3.3 Grading the Level of Evidence for each Intervention

For each of the 45 studies summarized in Table 3.4, we graded the level of evidence associated with each intervention. In Table 3.5, each intervention's level of evidence is assigned a grade of (a) strong, (b) moderate, (c) limited, or (d) minimal according to the criteria discussed in Section 3.2.6.

Table 3.5: Levels of evidence for interventions. Note we use *I* and *C* to denote intervention group and control group, respectively. Additionally, *(-)* is used to denote no effect and *(+)* is used for improved effect. If not specified, *significant* means *p* is under 0.05.

Intervention Category	**Reference**	**Intervention Description**	**Outcomes & Significance**	**(Calc) Effect Size / Mean % Difference of Outcomes**	**Effect**	**Design**	**Quality**	**Evidence**
(A) Individual-focused interventions								
Assistive device	Majkowski et al. (1998)	I: with belt C: without belt	Isometric lifting force MPF (I vs C) paraspinal: not significant		Lumbar (-)	CCT (cross-over)	Low	Moderate
	Iwakiri et al. (2008)	I: with standing aid C: without the aid	Post-work VAS (I vs C) overall: significant	Post-work VAS (I vs C) short: 16.4% increase tall: 21.7% decrease	Overall (+)	RCT (cross-over)	Low	
	Lotz et al. (2009)	I: with PLAD C: without PLAD	Percent change in RMS Percent change in MDF (I vs C) thoracic ES, lumbar ES: significant Heart rate Maximum extension strength (I vs C) global: not significant RPE Back endurance time (I vs C) global: significant	Percent change in RMS (I vs C) thoracic ES: 78.8% decrease lumbar ES: 70.5% decrease Percent change in MDF (I vs C) thoracic ES: 97.3% decrease lumbar ES: 98% decrease RPE (I vs C) global: 8.8% decrease Back endurance time (I vs C) global: 19.3% decrease	Lumbar (+) Overall: (+)(-)	RCT (cross-over)	High	
	Rashedi et al. (2014)	I1: WADE & 1.1kg payload I2: WADE & 3.4kg payload I3: WADE & 8.1kg payload C1: 1.1kg payload C2: 3.4kg payload C3: 8.1kg payload	Borg CR10 (I2 vs C2) & (I3 vs C3) upper arm, shoulder, low back: significant (I1 vs C1) upper arm, shoulder, low back: not significant Temporal change in nRMS (I3 vs C3) L TB: significant R TB: lower (I1, I2, I3 vs C1, C2, C3) R AD: significant L AD: not significant R ILL: significant	Borg CR10 (I2 vs C2) upper arm: 54% decrease shoulder: 34% decrease (I3 vs C3) upper arm: 57% decrease shoulder: 45% decrease Temporal change in nRMS (I3 vs C3) L TB: 40% decrease (I1, I2, I3 vs C1, C2, C3) R & L AD: 36-56% decrease R ILL: 31-88% increase	Upper extremities (+) Lumbar (+)	CCT (cross-over)	Low	
	Miura et al. (2018a)	I: with HAL C: without HAL	Post-work VAS (I vs C) lumbar: significant	Post-work VAS (I vs C) lumbar: 47.2% decrease	Lumbar (+)	CCT (cross-over)	Low	
	Miura et al. (2018b)	I: with HAL C: without HAL	Post-work VAS (I vs C) lumbar: significant	Post-work VAS (I vs C) lumbar: 33.3% decrease	Lumbar (+)	CCT (cross-over)	Low	

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Table3.5 – *Continued from previous page*

Intervention Category	Reference	Intervention Description	Outcomes & Significance	(Calc) Effect Size / Mean % Difference of Outcomes	Effect	Design	Quality	Evidence
	Bazazan et al. (2019)	I: posture correction-based device C: no device	MFI-20 after intervention (I vs C) physical, general: significant reduced activity, reduced motivation: not significant Change in MFI-20 (post-pre) (I) physical: significant general, reduced activity, reduced motivation: not significant (C) not significant	Percent change in MFI-20 from baseline 6-month follow-up: (I vs C) physical: 502.8% decrease general: -376% increase (I) physical: 16.7% decrease 12-month follow-up: (I vs C) physical: 576.2% decrease general: -424.3% increase (I) physical: 18% decrease	Overall (+)	CCT	High	
Posture variation	Meyer and Radwin (2007)	I: prone posture C: stoop posture W1: after 1st work W2: after 2nd work	W1: Percent change in RMS from baseline (I vs C) TZ: no change in I & C ES: 53.7% significant increase in C, 5.59% not significant decrease in I hamstring: 18.5% significant increase in C, 5.29% not significant decrease in I Percent change in MPF from baseline (I vs C) TZ: 4.13% significant decrease in C, 3.89% significant decrease in I ES: not available hamstring: 12.6% significant decrease in C, 5.1% not significant decrease in I W2: not significant change	W1: Percent change in RMS from baseline (I vs C) ES: 110.4% decrease hamstring: 128.6% decrease Percent change in MPF from baseline (I vs C) TZ: -5.8% increase hamstring: -59.5% increase	Upper extremities (-) Lumbar (+) Lower extremities (+)	RCT (cross-over)	High	Minimal
	Thorp et al. (2014)	I: stand-sit, interchanging every 30-min C: sit	CIS20-R on day 5 (I vs C) total: significant subjective feeling, decreased physical activity: lower MAF-GFI on day 5 (I vs C) not significant	CIS20-R on day 5 (I vs C) total: 22.3% decrease	Overall (+)	RCT (cross-over)	High	
	Tanoue et al. (2016)	I: dynamic balance chair C: standard office chair	Post-work VAS (I vs C) lumbar: significant	Post-work VAS (I vs C) lumbar: 27% decrease	Lumbar (+)	RCT (cross-over)	High	
	Son et al. (2018)	I1: footrest at 5% of body height I2: footrest at 10% of body height I3: footrest at 15% of body height C: no footrest	MDF ratios (post/pre) (I2, I3 vs C) lumbar: higher (I1 vs I2) lumbar: lower MAR ratios (post/pre) (I2, I3 vs C) lumbar: lower (I1 vs I2) lumbar: higher	No means, std dev, or correlations for post-MDF and post-MAR	Lumbar (+)	RCT (cross-over)	High	
	Lee et al. (2018)	I: with footrest C: no footrest	MDF (I vs C) R ES: not significant Amplitude (I vs C) similar pattern with MDF		Lumbar (-)	RCT (cross-over)	High	

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Table3.5 – *Continued from previous page*

Intervention Category	Reference	Intervention Description	Outcomes & Significance	(Calc) Effect Size / Mean % Difference of Outcomes	Effect	Design	Quality	Evidence
	Bao and Lin (2018)	I1: 60-m sit & 60-m stand I2: 80-m sit & 40-m stand I3: 90-m sit & 30-m stand I4: 105-m sit & 15-m stand	Change in MDF (I1 vs I4) L ES: significant (p <0.1) L TZ, R TZ, R ES: not significant within groups (I1 vs I2, I3) & (I2 vs I3, I4) & (I3 vs I4) L TZ, R TZ, L ES, R ES: not significant within groups	Change in MDF (I1 vs I4) L ES: -73.8% increase	Upper extremities (-) Lumbar (-)	RCT (cross-over)	High	
	Baker et al. (2018)	I: standing with movement C: standing	Amplitude (I vs C) RF: significant ES, BF, TA: not significant MDF (I vs C) RF, ES, BF, TA: not significant	Percent change in amplitude (I vs C) RF: -312.6% decrease	Lumbar (-) Lower extremities (-)	RCT (cross-over)	High	
Mats/shoe-insoles	Kim et al. (1994)	I1: thin mat I2: thick mat C: concrete surface	MDF shift (I1 vs C) ES: lower (I2 vs C) ES: not significant (I1, I2 vs C) GAS, TA: not significant (I1 vs I2) GAS, ES, TA: lower	No means, std dev, and correlations	Lumbar (+) Lower extremities (-)	RCT (cross-over)	Low	Minimal
	Madeleine et al. (1997)	I: soft surface C: hard surface	Time duration of MVC Moment Slope of MPF Slope of RMS (I vs C) R SL: not significant		Lower extremities (-)	CCT (partial cross-over)	High	
	Kelaher et al. (2000)	I: semi-rigid orthotics C: regular shoe insoles	A-P sway speed (cm/s) Lateral sway speed (cm/s) Total sway speed (cm/s) Sway speed ratio (A-P/lateral) (I vs C) not significant		Overall (-)	CCT (cross over)	Low	
	Cham and Redfern (2001)	I1-I6: six types of floor mats with different material properties (Mat B-G) C: hard floor	Borg CR10 during 3rd-4th hr overall: not significant (I1-I4 vs C) & (I2 vs I5) whole leg: lower (I5, I6 vs C) & (I5 vs I6) whole leg: not significant Change in MDF (I1-I6 & C) R TA, R SL, R & L ES, R hamstring, R quadriceps: not significant	Borg CR10 during 3rd-4th hr No means, std dev, or correlations	Overall (-) Lower extremities (+) (-) Lumbar (-)	RCT (cross-over)	Low	
	King (2002)	I1: floor mat I2: shoe in-soles I3: shoe in-soles & floor mat C: hard floor	Rating (1-5) after exposure (I1, I2, I3 vs C) general, leg: significant (I2, I3 vs I1) & (I2 vs I3) general, leg: not significant	Rating (1-5) after exposure (I1 vs C) & (I2 vs C) general: 28.1% decrease leg: 31.8% decrease (I3 vs C) general: 31.8% decrease leg: 37.4% decrease	Overall (+) Lower extremities (+)	RCT (cross-over)	Low	
Exercise	Hamberg-van Reenen et al. (2009)	I: 8-week resistance training, twice per week C: no training W1: assembly W2: lifting	MVE P(50) (I vs C) not significant W1: Change in mean slope of MPF (I vs C) back: not significant W2: shoulder: no fatigue detected		Lumbar (-)	RCT	High	Minimal

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Intervention Category	Reference	Intervention Description	Outcomes & Significance	(Calc) Effect Size / Mean % Difference of Outcomes	Effect	Design	Quality	Evidence
	de Vries et al. (2017)	I: 6-week exercise C: wait-list	Post-intervention FAS (I vs C) overall, need for recovery: not significant Change in FAS Change in need for recovery (I) post I, 6-week, 12-week: significant (C) not significant Percentage of recovered participants post-intervention (I vs C) significant	Change in FAS (I) post I: -0.55 6-week: -1.02 12-week: -0.92 Change in need for recovery (I) post I: -0.32 6-week: -0.53 12-week: -0.6 Percentage of recovered participants post-intervention (I vs C) 219.5% increase	Overall (-) (+)	RCT	High	
Relaxation therapy	Keller et al. (2012)	I1: 5-week 30-min massages I2: 10-week 30-min massages C: no massage	Change in VAS from baseline (I1 vs I2) & (I1, I2, vs C) after 5-week, after 10-week: not significant change (I1) & (I2) after 5-week: not significant change after 10-week: significant (C) after 5-week, after 10-week: not significant VAS (I1 vs I2) after 5-week: not significant after 10-week: significant (I1, I2, vs C) after 5-week, after 10-week: not significant	Change in VAS from baseline (I1) after 10-week: 25% decrease (I2) after 10-week: 50% decrease VAS (I1 vs I2) after 10-week: 0.6	Overall (-)	RCT	High	Minimal
	Rapolienė et al. (2016)	I1: geothermal I2: music C: control	Change in MFI (I1, I2 vs C) & (I1 vs I2) No comparison made (I1) & (C) physical, general: significant (I2) physical, general: not significant MFI after 2-week (I1 vs C) physical, general: significant (I1 vs I2) physical, general: not significant (I2 vs C) no comparison made	Change in MFI (I1) physical: 0.9 general: 1.2 (C) physical: -0.9 general: -0.6 MFI after 2-week (I1 vs C) physical: 0.7 general: 1.1	Overall (+)	RCT (partial cross-over)	Low	
Garment change	Chan et al. (2016)	I: long-sleeve compression top and short-leg compression pants C: no compression garments	Perceived fatigue (I vs C) not significant Change in perceived fatigue (I) & (C) post- from pre-exercise, 24 hr from post-exercise: significant	Change in perceived fatigue (I) post- from pre-exercise: 128% increase 24 hr from post-exercise: 56.1% decrease (C) post- from pre-exercise: 97.4% increase 24 hr from post-exercise: 50.6% decrease	Overall (-)	RCT (cross-over)	High	Moderate
	Jensen et al. (2016)	I: 5C cooling C: 32C thermal neutral	Time to fatigue (I vs C) forearm: not significant		Upper extremities (-)	RCT (cross-over)	Low	
Oral rehydration	Ishikawa et al. (2010)	I: oral rehydration C: free-choice of favorite drink	VAS after work (I vs C) significant	VAS after work (I vs C) 0.2	Overall (+)	RCT (cross-over)	High	Limited

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Intervention Category	**Reference**	**Intervention Description**	**Outcomes & Significance**	**(Calc) Effect Size / Mean % Difference of Outcomes**	**Effect**	**Design**	**Quality**	**Evidence**
Chemical supplements	Suh et al. (2012)	I: intravenous Vitamin C C: normal saline	Rating (0-10) post-intervention (I vs C) after 2 hr, 24 hr: all, lower VC: significant	Percent change in rating (I vs C) after 2 hr: all: -130.6% decrease lower VC: -107.9% decrease after 24 hr: all: -448.4% decrease lower VC: 830.5% decrease	Overall (+)	RCT	High	Limited
Micro-current stimulation	Kang et al. (2015)	I1: microcurrent stimulation I2: transcutaneous electrical nerve stimulation C: only rest	Post-intervention MDF Post-intervention muscle tones (I1 vs C) R & L ES: significant (I2 vs C) R & L ES: not significant MDF Muscle tones (I1) & (I2) & (C) R & L ES: significant Post-intervention CK & LDH (I1, I2 vs C) not significant CK & LDH (I1) & (I2) & (C) significant	Percent change in MDF (I1 vs C) R ES: 159.67% increase L ES: 116.1% increase Percent change in muscle tones (I1 vs C) R ES: 58.4% increase L ES: 59.3% increase	Lumbar (+)	RCT	High	Limited
(B) Workplace-focused interventions								
Task variation	Evstigneeva et al. (2012)	I1: Handgrip test with passive perception of audio stimuli I2: Handgrip test with active stimuli discrimination I3: Handgrip test with active stimuli discrimination following motor response	Borg CR10 (I3 vs I1) lower	No means, std dev and correlations	Overall (+)	CCT (cross-over)	High	Moderate
	Mathiassen et al. (2014)	I1: six 7 min bouts of repetitive reaching task with interrupted breaks, recall and orally report the last letter. I2: six 7 min bouts of repetitive reaching task with interrupted breaks, recall and orally report the last two letters. I3: six 7 min bouts of repetitive reaching task with interrupted breaks, recall and orally report the last three letters.	During work & break: Change in Borg CR10 Change in aching-SOFI Change in amplitude Change in MPF not significant Post-work 1 hr: Change in Borg CR10 (I1 vs I3) neck & shoulder: higher Change in aching-SOFI (I2 vs I3) higher (p <0.1) Change in spent-SOFI (I1 vs I3) higher Change in amplitude TZ: not significant	Post-work 1 hr: Change in Borg CR10 Change in aching-SOFI Change in amplitude No means, std dev or correlations	Overall (+) Upper extremities (+) (-)	CCT (cross-over)	High	
	Luger et al. (2015)	I1: 1 hr repetitive Pegboard task with passive 1 min rest I2: 1 hr repetitive Pegboard task with active 1 min box-replacement C: 1 hr continuous repetitive Pegboard task	MDF (I1 vs C) MTD whole: lower ARV (I1, I2 vs C) not significant	No means, std dev and correlations	Upper extremities (-)	CCT (cross-over)	High	

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Intervention Category	**Reference**	**Intervention Description**	**Outcomes & Significance**	**(Calc) Effect Size / Mean % Difference of Outcomes**	**Effect**	**Design**	**Quality**	**Evidence**
	Luger et al. (2016)	I1: low rotation frequency between dynamic box-lifting and static pick-and-place I2: high rotation frequency I3: self-selected rotation frequency	SOFI not significant Change in Borg CR10 (I1 vs I3) R shoulder: significant ARV (I2 vs I3) MDA: significant MDF not significant	Change in Borg CR10 (I1 vs I3) R shoulder: 37.5% increase ARV (I2 vs I3) MDA: 909.3% increase	Overall (-) Upper extremities (+) (-)	CCT (cross-over)	High	
Tools redesign	Rempel et al. (2009)	I1: foot lever I2: drill press C: usual method	Rating (0-5) (I1 vs C) shoulder, hands & forearm, low back: significant neck, leg: not significant (I2 vs C) neck, shoulder, hands & forearm, low back, leg: significant (I1 vs I2) leg: significant neck, shoulder, hands & forearm, low back: not significant	Rating (0-5) (I1 vs C) shoulder: 72.5% decrease hands & forearm: 74.3% decrease low back: 62.3% decrease (I2 vs C) neck: 50% decrease shoulder: 60.7% decrease hands & forearm: 76.2% decrease low back: 80% decrease leg: 76.5% decrease (I1 vs I2) leg: 71.5% decrease	Upper extremities (+) Lumbar (+) Lower extremities (+)	RCT (cross-over)	High	Minimal
	Kim et al. (2014)	I1: LHG I2: HHG C: SHG	MDF (I1 vs C) upper TZ: significant middle DL, rhomboid, infraspinaturs: not significant (I2 vs C) upper TZ, middle DL, rhomboid, infraspinaturs: not significant (I1 vs I2) upper TZ, middle DL, rhomboid, infraspinaturs: significant	MDF (I1 vs C) upper TZ: 0.7 (I1 vs I2) upper TZ: 0.8 middle DL: 0.7 rhomboid: 1.0 infraspinaturs: 0.9	Upper extremities (+)	RCT	High	
	Allahyari et al. (2016)	I: adjustable vertical loom C: low-height vertical loom	RMS MDF (I) & (C) no fatigue detected Borg CR10 (I vs C) not significant		Upper extremities (-)	CCT (cross-over)	High	
Rest break	Crenshaw et al. (2006)	I1: rest every 20-min I2: forearm extensions every 20-min	Amplitude MDF Borg CR10 (I1 vs I2) forearm: not significant		Upper extremities (-)	CCT (cross-over)	High	Minimal
	Mailey et al. (2017)	I1: 1-2min short, frequent break, stand/move every 0.5 hr I2: long, planned break, two 15-min break each workday	FSI (I1 vs I2) not significant Proportion of improved (I1 vs I2) interference: higher	Proportion of improved No means or std dev	Overall (-)(+)	RCT	High	

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Table3.5 – *Continued from previous page*

Intervention Category	**Reference**	**Intervention Description**	**Outcomes & Significance**	**(Calc) Effect Size / Mean % Difference of Outcomes**	**Effect**	**Design**	**Quality**	**Evidence**
Participatory ergonomics	Brandt et al. (2018)	I: 3-phase workshops C: reading handouts	Rating (0-5) (I vs C) after 3-month, after 6-month: significant (I) significant	Percent change in rating from baseline (I vs C) after 3-month: 103.8% decrease after 6-month: 171.2% decrease (I) after 3-month: 0.7% decrease after 6-month: 13.4% decrease	Overall (+)	RCT	High	Minimal
	Haukka et al. (2008)	I: active group work C: no training	Rating (1-7) (I vs C) not significant		Overall (-)	RCT	High	
Change work pace	Bosch et al. (2011)	I1: 2 hr pick and place task at high work pace I2: 2 hr pick and place task at low work pace	Increase rate of Borg CR10 Decrease rate of MVF (I1 vs I2) Neck/shoulder: not significant Amplitude MPF no fatigue detected		Upper extremities (-)	RCT (cross-over)	Low	Minimal
(C) Multiple interventions								
Mats/shoe-insoles & Posture variation	Hansen et al. (1998)	C1: clogs I1: soft shoes C2: hard floor I2: soft floor W1: Standing W2: Standing/walking	W1: Change in RMS (C1C2 vs I1C2) & (C1C2 vs I1I2) & (C1I2 vs I1C2) & (I1C2 vs I1I2) significant (C1C2 vs C1I2) & (C1I2 vs I1I2) not significant Change in MPF paravertibral: not significant between any two groups above W2: no fatigue detected	W1: Change in RMS (C1C2 vs I1C2) 4.1% decrease (C1C2 vs I1I2) 17.5% increase (C1I2 vs I1C2) 12.2% decrease (I1C2 vs I1I2) 22.5% increase	Lumbar (-)(+)	CCT (cross-over)	Low	Limited
	Garcia et al. (2016)	I1: standing on an antifatigue mat I2: standing on a hard floor I3: walking on a treadmill	MTF amplitude (I1, I2 vs I3) GAS-SL: lower MTF duration (I1, I2 vs I3) GAS-SL: higher	No means, std dev and correlations	Lower extremities (+)	RCT (cross-over)	High	
Change work pace & Rest break & Change work duration	Mathiassen and Winkel (1996)	I1: 100 or 120 MTM I2: added 20-min of active/passive breaks every 2h I3: 2, 4 or 6 hr of work duration	During work: Percent change in amplitude (I1: 100 vs 120 MTM) significant Borg CR10 (I2 vs I1-120 MTM) not significant (I2 vs I1-100 MTM) higher (I3) higher for longer duration During recovery: Percent change in amplitude Borg CR10 not significant	During work: Percent change in amplitude (I1: 100 vs 120 MTM) 281.8% decrease Borg CR10 (I1: 100 vs 120 MTM) 125% decrease	Shoulder (+)	CCT (cross-over)	Low	Minimal

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Table3.5 – *Continued from previous page*

Intervention Category	**Reference**	**Intervention Description**	**Outcomes & Significance**	**(Calc) Effect Size / Mean % Difference of Outcomes**	**Effect**	**Design**	**Quality**	**Evidence**
Posture variation & Rest break	Garcia et al. (2018)	I1: short standing period I2: medium standing period I3: long standing period R1: remain seated on an armchair R2: 3 activities (pedaling while seated, elevating legs and resting them stretched and supported while seated, one leg balancing and stepping on toes 15 times with each leg while standing)	MTF amplitude MTF duration GAS-SL: not significant		Lower extremities (-)	RCT (cross-over)	High	Limited
Tools redesign & Rest break	Callegari et al. (2018)	I1: wrist support I2: resting pauses C: control	Borg CR10 after 4 hr (I1, I2 vs C) & (I1 vs I2) not significant Percentage of the fatigued after 1-hr, after 4-hr: (I1 vs C) & (I2 vs C) total: significant (I1, I2 vs C) & (I1 vs I2) TZ: not significant EDC: highest 4-hr vs 1-hr: (I1) BB: significant (I2) EDC: significant	Percentage of the fatigued after 1-hr: (I1 vs C) total: 9% decrease (I2 vs C) total: 10.4% decrease after 4-hr: (I1 vs C) total: 18.5% decrease (I2 vs C) total: 21.5% decrease 4-hr vs 1-hr: (I1) BB: 18.2% decrease (I2) EDC: 26.3% decrease	Upper extremities (+) shoulder (-)	RCT (cross-over)	Low	Minimal

VAS: Visual Analog Scale, CIS: Checklist Individual Strength, FAS: Fatigue Assessment Scale, MAF: Multidimensional Assessment of Fatigue,
FSI: Fatigue Symptom Inventory, MD/PF: Median/Mean Power Frequency, (n)RMS: (normalized) Root Mean Squared, MTF: Muscle Twitch Force,
MAR: Muscle Activity Ratio, ARV: Average Rectified Value, SD: Standard Deviation, CK: Creatine Kinase Lactate, LDH: Lactate Dehydrogenase,
ES: Erector Spinae, TZ: Trapezius, SL: Soleus, GAS: Gastrocnemius, BB: Biceps Branchii, TA: Tibialis Anterior, R/BF: Rectus/Biceps femoris, DL: Deltoid
RPE: Rate of Perceived Exertion, BURMS: Brunel Mood State Questionnaire, GFI: Global Fatigue Index, MTM: Methods-time measurement,
ILL: Iliocostalis Lumborum pars Lumborum, MTD: M. Trapezius Descendens, MDA: M. Deltoid Acromialis, EDC: Extensor Digitorum Communis.
MAD: Median Absolute Deviation, MVC/F: Maximum Voluntary Contraction/Force, SOFI: Swedish Occupational Fatigue Inventory.

From Table 3.5, one can make the following observations based on the levels of evidence for each intervention. First, there were two interventions that presented moderate evidence for reducing fatigue using assistive devices and task variation. Garment change also showed moderate evidence for having no effect on fatigue. The remaining 15 interventions had either limited or minimal evidence. The lower ratings for these 15 interventions were because (a) the individual studies were found to be of low quality using the PEDro score; (b) the intervention of interest was examined only in one study; and/or (c) inconsistencies were found in the conclusions of effects. In the following section, we discuss in greater detail the interventions that had moderate, limited, or minimal evidence.

3.4 Discussion and Conclusions

3.4.1 Interventions with Moderate Efficacy Evidence

Individual-focused interventions

Assistive devices. Seven studies concluded, with a moderate level of evidence, that using an assistive device can reduce fatigue. It can be hypothesized that assistive devices function by reducing the force requirements or increasing the strength capability of the worker, thus reducing the relative workload and ultimately the level of fatigue that develops. One high-quality RCT (Lotz et al., 2009) using multiple measurements, one low-quality RCT (Iwakiri et al., 2008), one high-quality CCT (Bazazan et al., 2019) and three low-quality CCTs (Rashedi et al., 2014; Miura et al., 2018b,a) that used subjective ratings presented positive effects. One low-quality CCT (Majkowski et al., 1998) that used isometric lifting force and mean power frequency as fatigue outcomes showed no effect. Fatigue of the upper extremities, the lumbar region, and the whole body were evaluated in this intervention category.

For the RCTs, Lotz et al. (2009) tested the effect of an on-body personal lift assist device (PLAD) which utilizes elastic energy to produce an assistive moment at the low back by transferring some of the forces to the shoulders, pelvis, and knees. The PLAD reduced the severity of erector spinae muscular fatigue during a 45-minute lifting session at a pace of six liftings/lowerings per minute as shown by the EMG median frequency and amplitude. Iwakiri et al. (2008) found that a standing aid can alleviate subjective fatigue for tall chefs but not short chefs based on subjects' subjective ratings.

A high-quality CCT conducted by Bazazan et al. (2019) examined the effect of a posture correction-based intervention (i.e., an electronic device designed to improve awkward trunk posture) on the occurrence of fatigue among control room operators. A significant positive effect was found on physical fatigue compared with effects observed in the control group based on questionnaire responses over a 12-week period (the intervention was performedtwice per day × 30-min). A similar device for posture correction, the wearable assistive device (WADE), can be hypothesized to affect the physical demands on the upper extremities during overhead work. In the study conducted by Rashedi et al. (2014), twelve male participants completed 10 minutes of simulated, intermittent overhead work with one of three loads with orwithout the WADE. From the ratings of perceived discomfort, which served as a sensitive muscle fatigue indicator according to the authors, participants experienced less fatigue on the upper arms and the shoulders after work when the WADE was used. However, the use of the WADE did not substantially influence EMG-based measures of fatigue. Similarly, Miura et al. (2018b) and Miura et al. (2018a) both found lower subjective lumbar fatigue when using the Care Support robot during repetitive lifting and snow-shoveling movements, respectively. These three studies were dependent on subjective ratings regarding for relatively short-duration tasks, all performed within 10 minutes, which is substantially shorter than a normal working duration. With recent developments in the advancement of exoskeleton technology, more assistive devices with embedded technology are being designed and evaluated. To date, these systems have shown positive effects in reducing fatigue development for the limited conditions tested; however, further work is needed to support their use as a successful fatigue intervention.

It has also been argued that back belt use can increase intraabdominal pressure, indirectly reducing the fatigue of the lumbar paraspinal muscles. Majkowski et al. (1998) conducted a study with a repeated-measures multivariate design and found that there was no effect of back belt use on in reducing fatigue of the lumbar paraspinal muscles when the participants performed 10-lift/minute × 20-minute sessions under two conditions (with and without the belt). Muscular fatigue was indicated by a reduction in median power spectral frequency values from EMG or a decrease in isometric force-generating capacity. However, no significant changes in either measure were detected.

In summary, although the assistive devices from the existing studies provided moderate evidence of a positive effect on reducing fatigue, more relevant field studies that use objective measures should be conducted to provide more support for this rating of evidence. All of the studies that used subjective ratings reported positive effects of assistive devices (Lotz et al., 2009; Iwakiri et al., 2008; Bazazan et al., 2019; Rashedi et al., 2014; Miura et al., 2018b,a), but those that used objective measures provided conflicting results (though the endurance time used in the study by Lotz et al. (2009) can be seen as an indirect measure of fatigue (Vøllestad, 1997)) (Lotz et al., 2009; Majkowski et al., 1998; Rashedi et al., 2014). Further, five of these seven studies used a work-period less than one hour, which is much less than an actual work period expected.

Garment changes. One high- and one low-quality RCT provided moderate evidence of no effect on fatigue reduction or recovery. Chan et al. (2016) found that wearing compression garments during a four-hour simulated manual work task and for 24 hours thereafter did not significantly reduce perceived fatigue compared to the effect of not wearing the garments. Similar results were found by Jensen et al. (2016), where the use of a cooling garment did not improve the time to functional fatigue compared to the results of a thermal-neutral condition.

Workplace-focused interventions

Task variations. Four high-quality CCTs provided moderate evidence for the positive effect of task variation on reducing fatigue of the upper extremities or the whole body. Three studies (Evstigneeva et al., 2012; Mathiassen et al., 2014; Luger et al., 2016) that involved subjective ratings show ed promising results. One study (Luger et al., 2015) provided evidence of no effect based on the median frequency and amplitude of EMG.

Compared with continuous work, task variation or rotation may create opportunities for the muscles to recover. The total exposure and the development of muscle fatigue may be reduced relative to the effects of repetitive or monotonous tasks (Mathiassen, 2006). Evstigneeva et al. (2012) found a lower fatigue rating in an active stimuli discrimination following a motor response (button press) condition when compared with passive perception of audio stimuli (listening) and active stimuli discrimination (counting) conditions during a motor task (i.e., a 12-minute handgrip test with four sequential oddball blocks). Mathiassen et al. (2014) conducted three sessions that consisted of six seven-minute bouts of reaching alternating with three minutes of memory test differing in difficulty between sessions (recalling and orally reporting the last, two last or three last letters). No significant effects of mental tasks were found during the work session or break using either the subjective ratings or objective measurements, but at 1-hour postwork, subjective ratings for the most difficult mental task between fatiguing work bouts recovered significantly more than for the easiest mental task based on subjective ratings. Luger et al. (2016) tested four one-hour rotations scheduled at two low frequencies (rotating every 30 minutes), one high frequency (rotating every six minutes), and one self-selected frequency of job rotation for a dynamic box-lifting task and a relatively static pick-and-place task. Task rotation frequency was found to have no significant effect, but the self-selected rotation schedule resulted in lower development of perceived fatigue. In a study with contrasting results, Luger et al. (2015) had individuals perform three one-hour repetitive pegboard tasks in five continuous one-minute interrupted breaks and five active one-minute box-replacement task conditions. The hypothesized positive effect was not supported by the EMG results even with the consideration of the bias caused by changes in postures. Limited sample size and the sensitivity of EMG measures for low-intensity work were questioned by the authors.

These results encourage further research into combinations of physical and mental tasks in an occupational context. Though the subjective measures provided significant positive effects, the results from objective measures did not indicate fatigue during repetitive work or show a significant effect of task variation. Different frequencies of rotation, posture changes, various types of job tasks and effective fatigue measurement may need to be reconsidered to identify an effective combination. In addition, three of the studies in this intervention category had a work duration over one hour, and no obvious effect difference was found related to the length of work.

3.4.2 Interventions with Limited Efficacy Evidence

Individual-focused interventions

Oral rehydration. One high-quality RCT provided a limited level of evidence. Ishikawa et al. (2010) showed a positive effect of oral rehydration. Aircraft cargo loaders completed loading tasks on two summer days. One group was restricted to oral rehydration solution (ORS) intake and the other group had free choice of their favorite drink (FAD). Ratings on a fatigue visual analog scale were significantly lower on the ORS intake days than on the FAD intake days, which suggests that the intake of ORS during outdoor work in a hot environment could be effective for fatigue reduction.

Chemical supplements. One high-quality RCT reported the prevention of fatigue through the intake of chemical supplements. Vitamin C has shown a clinical value in its role as an antioxidant. Suh et al. (2012) showed that administration of high-does intravenous vitamin C reduced fatigue significantly more than placebo in office workers, especially in the subjects who had lower baseline levels of vitamin C.

Microcurrent stimulation One high-quality RCT evaluated the effect of microcurrent stimulation. It is hypthesized that microcurrent stimulation can induce cell responses in damaged tissues through bioelectricity to aid tissue healing (Cho et al., 2007). Kang et al. (2015) suggested that microcurrent stimulation was effective for recovery from cumulative muscle fatigue induced by repetitive lifting and lowering work while transcutaneous electrical nerve stimulation (TENS) had no effect, when compared to the results of the control group of participants who laid prone on the floor for 20 minutes. The temporal increase in local circulation was not sufficient to have a significant effect on muscle fatigue recovery through this stimulation of TENS.

Multiple Interventions

Mats/shoe-insoles & posture variation. One high-quality RCT (Hansen et al., 1998) and one low-quality CCT (Garcia et al., 2016) provided limited evidence for the combined effect of these interventions. Hansen et al. (1998) found no significant effect of mat use and shoe softness during either prolonged standing or standing/working in an upright position; however, the EMG-signs of lumbar fatigue were greater during the standing condition compared to the standing/walking condition. Garcia et al. (2016) showed that walking can partially attenuate the long-lasting weakening of muscle twitch force induced by standing on a hard floor and on an antifatigue mat. These two studies provide consistent evidence of a combined positive effect of posture variation (standing/walking) while using mats/shoe insoles based on objective measurements (i.e., EMG and MTF), although both individual interventions produced evidence rated as a minimal level.

Posture variation & rest breaks. Because only one high-quality RCT evaluated the combination of posture variation and a rest break and this study found no effect, there is limited evidence of no effect. Garcia et al. (2018) assessed the duration and amplitude of muscle twitch force during a five-hour simulated standing work with work-rest cycles with short, medium or long standing periods including passive or active breaks. No significant differences in fatigue outcomes in the lower extremities were found between conditions. This study showed that posture variation may not have an advantage in reducing fatigue severity when combined with a rest break.

3.4.3 Interventions with Minimal Efficacy Evidence

Posture Variations. While seven RCTs with high methodological quality were conducted that considered the effect of changing postures during prolonged or repetitive work on the reduction in physical fatigue, the results of these studies were inconsistent, leading to a rating of a minimal level of evidence. Four studies (Meyer and Radwin, 2007; Thorp et al., 2014; Tanoue et al., 2016; Son et al., 2018) showed positive effects while three studies (Lee et al., 2018; Baker et al., 2018; Bao and Lin, 2018) presented no effects. Both studies (Thorp et al., 2014; Tanoue et al., 2016) that used subjective ratings of fatigue demonstrated positive effects, but the remaining studies that applied EMG had conflicting results. The locations of fatigue investigated included the upper extremities, the lumbar region, the lower extremities and the whole body.

A “combination of postures” lowers the static load on postural muscles compared to the effects of sustained sitting or standing postures. Physiologically, frequently alternating between postures reduces muscle fatigue via sustained activation of low threshold motor units while prolonged postures cause low-level static muscle loading (Hagg, 1991). Meyer and Radwin (2007) evaluated fatigue in the shoulders, lumbar region and legs in stooped and prone postures during a simulated 30-minute agricultural harvesting task. Localized fatigue provided evidence in favor of the prone posture based on the mean power frequency and amplitude of EMG. Thorp et al. (2014) conducted two five-day × eight-hour/day experimental conditions in an equal, randomized order among overweight/obese office workers who performed their usual occupational tasks either in a seated work posture or interchanging between a standing and seated work posture every 30 minutes using an electric, height-adjustable workstation. Through self-administered questionnaires, participants' total fatigue score was significantly lower in the sit-stand condition. Tanoue et al. (2016) compared a dynamic seated balance chair compared with a standard office chair. Healthy adults performed a 30-minute Kraepelin test (i.e., a single-digit sum) under these two conditions, and lumbar fatigue was significantly lower in the seated postures that encourage pelvic movements based on a postwork VAS. Son et al. (2018) applied a footrest at 10% of body height condition and found that two-hour prolonged standing with light office tasks caused the lowest muscle fatigue and placed the lowest load on the lumbar region with the lowest pain development in the 10% condition compared to the results when the footrests were at 5% or 15% of body height.

In contrast to Son et al. (2018), Lee et al. (2018) and Baker et al. (2018) both found no effects of a footrest, when compared to the effects of no footrest during a two-hour prolonged standing computer work session. They suggested a need for optimal footrest use conditions and an increased sample size. Bao and Lin (2018) found a longer standing schedule (i.e., 0-minute sitting and 60-minute standing) may have a tendency to result in less lumbar fatigue, and the shoulder and low back muscle activities did not differ significantly through a sit-stand workstation that introduces trunk posture changes.

Note that both subjective ratings and objective measures showed inconsistencies regarding the effect of posture variation. As a minimal level of evidence was obtained, more studies that use other measurement methods, such as postural sway (a potentially suitable physical fatigue measurement for long periods of low-load tasks (Yung and Wells, 2017), should be considered to test the correlation and/or reliability among the objective outcomes. Most of the studies in this category had a duration over two hours except for two studies that included experiments of 30 minutes (Meyer and Radwin, 2007; Tanoue et al., 2016), and no obvious distinction of effect was found based on the duration.

Mats or shoe insoles. Five studies provided minimal evidence of mats or shoe-insoles' efficacy on lumbar, lower extremity, or whole body fatigue for prolonged standing work. Three low-quality RCTs (Kim et al., 1994; Cham and Redfern, 2001; King, 2002) had positive effects, while one high (Madeleine et al., 1997) and one low-quality CCT (Kelaher et al., 2000) showed no effects. The prolonged standing periods ranged from two hours and were assessed over an

18-week trial. The lower extremities showed a larger benefit when the standing duration was longer. All subjective ratings (Cham and Redfern, 2001; King, 2002) showed positive effects; however there were limited significant effects in EMG or postural sway outcomes.

In a study by Kim et al. (1994), localized muscle fatigue in the erector spinae was reduced (based on EMG for a sample of only five subjects) when standing on two mat surfaces compared to the fatigue associated with standing on a concrete surface. However, localized muscle fatigue in the leg was not relieved. Ten participants stood for four hours on each of seven floor conditions in a study by Cham and Redfern (2001), and significant differences were found for leg fatigue between the hard floor and mat conditions in the third to fourth hour of prolonged standing. King (2002) found significant differences in general and lower extremity fatigue between standing on a hard floor and a floor mat using shoe in-soles, and using both shoe in-soles and a floor mat. Madeleine et al. (1997) evaluated the effects of standing on hard and soft surfaces using time duration of MVC, moment, and EMG during a two-hour prolonged standing period, and Kelaher et al. (2000) assessed the prefabricated orthotics on fatigue resistance through the motion parameters of center of pressure (CoP) (two hours/week for 18 weeks). Neither found a significant positive effect.

Exercise. Two high-quality RCTs resulted in minimal evidence of efficacy due to their inconsistent findings. de Vries et al. (2017) set up a six-week × one-hour × three times/week low-intensity running sessions, and compared the results with those of the wait-list control group. Based on analyses of covariance, the exercise group reported lower overall fatigue than the control group according to per-protocol analyses, but no significant effect in the intention-to-treat analyses was found. In contrast, Hamberg-van Reenen et al. (2009) compared the eight-week × twice/week resistance training group with a no training group in a convenience sample of healthy workers. During the assembly work task, no significant effect was found for the median frequency or amplitude of EMG. Shoulder fatigue was not detected during the lifting task. While these two experiments had similar total exercise intervention durations (over a month), they had different exercise modalities (running vs. resistance training), which may have resulted in the different effects. Further studies are needed to evaluate a larger set of training protocols and a combination of objective and subjective fatigue measures.

Muscle relaxation. One high- and one low-quality RCT provided minimal evidence of the effect of muscle relaxation. Keller et al. (2012) assessed the effect of massage therapy (30-minute/week × 5 or 10 weeks) on healthcare employees but no significant effects were observed compared with the effects observed in no massage group. Rapolienė et al. (2016) investigated the influence of high salinity geothermal mineral water bath (15-minute × 5 times/week × 2 weeks) on high-stressful seaman fatigue and significant effects were found in overall physical fatigue compared with the effects observed in the control group. Both studies used the subjective ratings but with two opposite effects. Due to the different types of work targeted in these two studies and two different types of relaxation therapies, it is hard to reacg a definite conclusion of an effect.

Workplace-focused interventions

Tool redesign. Three studies provided minimal evidence for the fatigue reduction effect of tool redesign. Two high-quality RCTs (Rempel et al., 2009; Kim et al., 2014) had positive findings, but one high-quality CCT (Allahyari et al., 2016) resulted in no fatigue being detected using EMG and no significant changes in subjective ratings. These studies considered fatigue of the upper extremities, lumbar region, and lower extremities.

Ergonomic workstation improvements are expected to reduce muscle fatigue by reducing the workload on the muscles or improving the working postures to minimize awkward positions, particularly for the arms and trunk. Rempel et al. (2009) investigated the effects of two intervention devices, an inverted drill press and a foot lever design, on regional body fatigue. Compared with the usual method of overhead drilling, construction workers' subjective ratings improved significantly in association with the redesigned tools. Kim et al. (2014) found that a table lower than elbow height can decrease shoulder muscle fatigue in sonographers, even during a work duration of 5 minutes. Allahyari et al. (2016) compared the muscle fatigue associated with traditional and adjustable vertical looms during a three-hour carpet weaving activity. However, no statistically significant conclusions could be drawn.

Although overall, tool redesign had a minimal level of evidence, the high-quality RCTs had significant positive results. In addition, most of the studies in this category, except for the study by Allahyari et al. (2016), showed consistent results across subjective and objective fatigue measures. Prevention through design remains a promising strategy for addressing fatigue, and future high-quality studies with longer durations should be performed to validate this effect.

Work Pace. Fatigue can be expected to develop at a faster rate for a fast work pace compared to a slower pace due to the physiological demand on the muscles and the inability to quickly supply sufficient oxygen to maintain the workload. Bosch et al. (2011) investigated the effect of work pace on fatigue during light assembly work. The participants performed a two-hour pick-and-place task at two work paces on two different days. However, the rate of increase in perceived fatigue and the rate of decrease in maximum voluntary force did not differ between the two work paces. No consistent evidence was found for muscle fatigue manifestation through EMG. Possible explanations were that variations in muscle forces and postures will have an effect on fatigue development, allowing for intermittent recovery throughout the task. More accurate objective fatigue measures may also be needed for low-intensity assembly work.

Rest Breaks. One RCT (Mailey et al., 2017) and one CCT (Crenshaw et al., 2006), both with high methodological quality studied the effect of rest breaks, but these studies obtained inconsistent results. Mailey et al. (2017) found that after eight weeks, more participants who took short, frequent breaks (stand/move for one to two minutes every half hour) reported significantly reduced fatigue interference compared to that of those who took longer, planned breaks in inactive females with full-time sedentary occupations that involved sitting each workday. Crenshaw et al. (2006) examined active (forearm extensions every 20 min) versus passive (rest every 20 min) pauses on fatigue in an one-hour computer mouse task. Neither subjective ratings nor EMG showed a significant effect. These two experiments used a different means of analysis; Mailey et al. (2017) compared percent of improved participants in the two groups, while Crenshaw et al. (2006) compared the direct fatigue outcome values for the two groups, which may have affected the outcome. In addition, the nature of the rest break and the work may influence the effectiveness.

Participatory ergonomics. Two high-quality RCTs provided minimal evidence of the effect of participatory ergonomics due to inconsistent effects on the basis of subjective ratings. Brandt et al. (2018) found that construction workers who participated in a three-phase set of workshops reported significantly lower general fatigue at three- and six-month follow-ups compared with a group assigned to read informational handouts. However, Haukka et al. (2008) did not find significant differences between an active group work condition and a no training condition at the three-month follow-up.

Multiple Interventions

Change in work pace, rest break & change work duration. One low-quality CCT found a positive effect of shortened work duration when compared to the effects of a lower work pace or break allowance. Mathiassen and Winkel (1996) investigated different combinations of work pace (120 or 100 methods-time measurement units (MTM)), break allowance (20 minutes of active or passive breaks added every two hours), and duration of the working day (two, four or six hours). A shorter work duration for the assembly work was found to be more effective in limiting acute fatigue than reduced work pace or increased break allowance.

Tool redesign & rest breaks. One low-quality RCT provided minimal evidence of a positive effect of the combination of support and rest breaks. Callegari et al. (2018) found that hand rest and wrist support can successfully reduce muscle fatigue in the upper limb muscles compared to the effects observed in the control group during a four-hour prolonged typing task, based on the percentage of fatigued participants.

3.4.4 Strengths and Limitations of this Systematic Review

This review systematically identified and appraised available evidence from interventions designed to reduce employee fatigue for employees. Because fatigue is a multifactorial condition that can lead to disease and production loss and affects a large number of workers worldwide, there is a need for proper intervention measures.

A macroergonomics framework was used to structure the analysis and explore the levels at which interventions should be targeted to achieve the greatest level of effectiveness.

Interventions were categorized as either having an individual focus, a workplace focus or multiple interventions. Individual-focused interventions included nine categories in 28 studies. Workplace-focused interventions includedfive categories in 12 studies. Multiple interventions include four categories in five studies. From the sample perspective, 25 out of 45 intervention studies included primarily young adults with an average age in the 20s-30s. Approximately half of the studies considered a balanced sex ratio in their experiments.

This review was the first to collect and synthesize data on existing interventions for physical fatigue for workplace-relevant conditions. The 45 systematically selected controlled trials were all published in peer-reviewed journals. Their study characteristics (i.e., study samples, experimental designs, location of fatigue, and work duration), methodological quality, effect on fatigue and level of evidence were extracted or evaluated through scientific approaches. The efficacy and explanations of each category of interventions were also described and discussed accordingly. However, there are still limitations of this review. The review focused on studies published in journals that were indexed in PubMed. The included studies focused on jobs in manufacturing, construction, farming, mining, office, and healthcare; however, not all of the relevant studies and coping measures may have been indexed in this database. Second, because of the heterogeneity regarding study samples, jobs, location of fatigue, types of interventions, outcome measures and study quality, no estimation of overall effect size could be made.

3.4.5 Implications for Future Research

Based on the sample characteristics, quality ratings, number of studies in each intervention category, and the design of experiments in existing studies, future intervention studies should focus on the following directions or aspects of physical fatigue at work:

(A) As most studies used convenience sampling for recruitment, there is a homogeneity of age groups between the 20s and 30s. It is important to conduct have evidence-based research using samples that are more representative of the true population in workplaces.

(B) Field studies with adequate sample sizes are needed for workplace-focused as well as individual-focused interventions with strong evidence of efficacy.

(C) High-quality RCTs are needed for all interventions, and authors of the resulting manuscripts should provide sufficient details documenting the study design.

(D) Reactive interventions are needed to facilitate recovery when fatigue has already occurred.

(E) Researchers are encouraged to include both (as appropriate) objective and subjective measures of fatigue and clearly specify the type or location of physical fatigue that was measured.

(F) Covariates and confounding factors should be measured and adjusted. This is especially true when the researchers are unable to randomize workers into their intervention and control groups.

(G) Empirical studies considering multiple risk factors for fatigue development are needed, as they may provide potential directions for intervention design.

(H) Ergonomics criteria (i.e., length of work exposure, evaluation in field conditions, and appropriate use of fatigue measurement based on work tasks) are needed for future evaluations of methodological quality of RCTs or CCTs.

Chapter 4

Conclusions

4.1 Dissertation Contributions

With the transition to advanced manufacturing environments, the use of innovative technology can result in significant changes on the shop-floor. It can reduce repetitive, mundane and dangerous work, but also has more dependencies on multiple skills, autonomy and responsibilities from workers to cooperate with the technology and respond to mass-customized products. It is important to understand how the role of labor is changing, safety-related impacts, and whether industries have corresponding safety and health management program in place. This dissertation captures one of the safety and health symptoms, physical fatigue, and aims to understand the current state of workers under advanced manufacturing environments and evaluate existing evidence-based interventions for the physical fatigue at work. The main contributions of this dissertation include: (a) presenting the prevalence of physical fatigue, its root causes and significant associated factors as well as the individual coping methods adopted by the survey participants in the manufacturing sector; (b) innovative use of statistical and data mining methods on specific types of survey questions to identify patterns for ergonomics findings; (c) systematic review of the existing controlled clinical trials of physical fatigue, grading their methodological quality, and assessing the levels of evidence on interventions.

In Chapter 2, the survey integrates fatigue measurement and multi-aspect risk factors to present an overview of the characteristics of workers, work and work environment in the U.S. manufacturing sector. Specifically, perceived fatigue, demographics, individual characteristics, work-related exposures, body parts affected, perceived fatigue causes and individual coping measures were measured and the relationships between fatigue and risk factors were explored. This is among the first surveys investigating worker physical fatigue and the aforementioned factors under advanced manufacturing environments. The high prevalence of fatigue found from the survey sets the foundation for continued studies of fatigue management in the manufacturing sector. The frequently affected body parts can indicate potential sensor and intervention locations for fatigue monitoring and mitigation, respectively. The significant associated factors, perceived fatigue causes and individual coping mechanisms may inform researchers and practitioners for future research in fatigue development and intervention.

Several statistical and machine learning methods were also applied for the first time to analyze specific types of survey questions for ergonomics implications. For example, to identify the threshold of fatigue, Gibbs sampling was first used to estimate the non-fatigued and fatigued distributions based on the continuous VAS value. This innovative use of such sampling may help achieve a data-driven decision rather than an arbitrary cut-off that may result in bias. Market basket analysis has also been first applied on "select all that apply" questions to discover frequent combinations of fatigue causes and individual coping measures. The use of this data mining method help identify patterns that may not easily be observed from descriptive statistics of individual items, where safety managers or practitioners may derive more insider views on why a set of root causes frequently occur together.

As fatigue was reported to be prevalent across sectors and can contribute to short-term and long-term adverse health outcomes, interventions are needed to lower the injury risks and lost productivity associated with fatigue. However, there is limited knowledge regarding existing intervention studies, their methodological qualities and the level of evidence on interventions. In Chapter 3, a comprehensive search of controlled clinical trials that mitigate physical fatigue at work was conducted to capture existing evidence-based interventions. This systematic review provides a fundamental knowledge base to facilitate the adoption of interventions by employees, which also aligns with the objective of NORA. From the practitioner perspective, interventions that had high level (i.e., strong or moderate) of evidence with a positive effect can be more likely to be tested and applied in the field. In the view of researchers, those had low level of evidence (i.e., limited or minimal) either need more high quality RCTs for consistent and robust conclusions of effects or are likely to be of no effect. This study may inform future technological adoptions and designs of interventions to mitigate physical fatigue at work.

Overall, the results of this work contribute to the design of fatigue monitoring, future research of fatigue development, determining whether specific interventions may be applicable for workers who undertake physical demanding tasks to mitigate their severity of fatigue while maintaining workplace productivity, and reducing the associated negative health outcomes.

4.2 Future Work

This dissertation provides a general picture of the current state of worker fatigue under advanced manufacturing environments and existing interventions for physical fatigue at work, using a survey and a systematic review approach, respectively. Based on this work, several research opportunities should be investigated and are highlighted as follows.

4.2.1 High Quality RCTs Examining Effects of Fatigue Interventions

Compared with previous fatigue prevalence studies across sectors, Chapter 2 found a high rate of fatigue among the surveyed U.S. manufacturing workers (57.9% of respondents indicated that they were somewhat fatigued during the past week). However, limited prescriptions of interventions were found through the results of coping mechanisms. In Chapter 3, a total of 45 controlled clinical trials examining 18 physical fatigue interventions within the occupational scope were included. Still, only two interventions were found to have moderate evidence on mitigating fatigue. The low level of evidence for most interventions was due to inconsistent conclusions on effects, limited number of studies, low quality studies or lack of RCTs. Thus, more high quality RCTs that examine effects of physical fatigue interventions at work are warranted to develop additional fatigue mitigation strategies and provide more evidence on the efficacy of such interventions. Specifically, reactive strategies are needed in addition to preventive methods to help efficient recovery as most existing clinical trials are preventive and there will be a lack of aid at field in case of fatigue. Field studies that recruit adequate samples from representative populations are preferred compared with lab studies to conclude the effect.

Covariates or confounders also need to be controlled or measured during experiments to reduce bias of the effect.

4.2.2 Occupational Ergonomics Criteria for Methodological Quality Evaluation

In Chapter 3, the methodological quality of each study was evaluated using a validated PEDro scale designed for clinical trials, however, as these studies are all within the scope of worker fatigue, several occupational ergonomics criteria can be considered. Specifically, whether the work duration in the protocol approximates field work hours, whether workers are exposed to the intervention for a sufficient time period or the lasting effect of the intervention is measured, and if the appropriateness of fatigue measurement is discussed. Future studies can design comprehensive occupational ergonomics criteria and test their validity and reliability. Due to a variety of job tasks and work populations, there is a lack of optimal settings for these criteria, the generalizability of these criteria should also be considered. In considering the aforementioned criteria, higher standards can be set for future clinical trials in the occupational ergonomics domain, and the methodological quality evaluation can be more specific.

4.2.3 Mental Fatigue during Physical Work and Universal Interventions

Chapter 2 and 3 focused primarily on physical fatigue, however, in practice, mental fatigue can also exist in certain physical work tasks such as repetitive workload and prolonged postures. As mental fatigue can be an important factor affecting work performance and resulting in safety issues, future research can investigate the development of mental fatigue during physical work, its prevalence and severity compared with physical fatigue, and the relationship between mental fatigue and injuries. In addition, the interaction between mental and physical fatigue should also be considered. If prevalent and significant, corresponding mental fatigue interventions should also be investigated to help minimize negative impacts. Explorations of universal approaches for both physical and mental fatigue can also be examined since these two types of fatigue may develop simultaneously at work. Comparing their rates of fatigue development and recovery through intervention studies may help further understand the fatigue development and recovery from both central and peripheral mechanisms.

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Appendices

Appendix A

Supplementary Materials

Supplementary documents for the survey study are available at: https://github.com/Michelle170/Fatigue-Survey-among-US-Manufacturing-Workers to allow researchers to replicate and build on study. The documents include: the pdf version of the survey, the complete survey responses with the removal of identification information, the procedures of getting the current results and other analysis results that are not presented in this paper for the sake of conciseness.

The workbooks documenting our analysis for the systematic review are available at: https://github.com/fmegahed/fatigue-interventions. The interested reader is encouraged to access our repository for more information/details on the work conducted in this systematic review.

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