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

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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 effects, including fatigue, have not been captured on an industry-wide scale. This paper presents results of a survey of U.S. manufacturing workers for the: prevalence of fatigue, its root causes and significant factors, and adopted individual fatigue coping methods. The responses from 451 manufacturing employees were analyzed using descriptive data analysis, bivariate analysis and Market Basket Analysis. 57.9% of respondents indicated that they were somewhat fatigued during the past week. They reported the ankles/feet, lower back and eyes were frequently affected body parts and a lack of sleep, work stress and shift schedule were top selected root causes for fatigue. In order to respond to fatigue when it is present, respondents reported coping by drinking caffeinated drinks, stretching/doing exercises and talking with coworkers. Frequent combinations of fatigue causes and individual coping methods were identified. These results may inform the design of fatigue monitoring and mitigation strategies and future research related to fatigue development.

1. Introduction and motivation

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 to "… (involve) 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 (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 was a workless manufacturing environment (i.e. lights out manufacturing facilities); however, advanced manufacturing 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 (see e.g., 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) broadening the workers' autonomy and responsibility as well as requiring new job duties (Waldeck, 2014). Third, the advancements in computation and sensing technologies is leading to smart factories, where workers will respond to mass-customized products (Hu, 2013) and have to

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be able to process and act upon large amounts of information.

Based on the above discussion, the transition to advanced manufacturing can potentially increase the physical and mental workload on workers. There is an increasing amount of literature suggesting that the increased workloads, which result in a higher prevalence of fatigue, continue to be a factor in advanced manufacturing settings. For examples, we refer the reader to: Brocal and Sebastián (2015), Romero et al. (2016), Ferjani et al. (2017), and Gust et al. (2017). In our estimation, these examples and the changing nature of jobs require a holistic analysis of the workers' states, from an occupational health and safety perspective and in the emerging era of advanced manufacturing.

Therefore, in this paper, we examine the impact of these changes on U.S. manufacturing workers in an attempt to answer the following research questions:

- What is the prevalence of (primarily physical) fatigue among U.S. advanced manufacturing workers?
- What are the main drivers for fatigue (if it is prevalent)?
- What are the coping measures of workers in combating fatigue (if it exists)?

These questions aim to understand fatigue prevalence from a macro-level among manufacturing workers, i.e., we are not interested in whether a worker is fatigued at this moment but rather over the span of their typical work week. To answer these questions, we created an online questionnaire that targeted 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 (advanced) manufacturing workplaces that are centered around human workers. In Section 2, we provide a definition for fatigue, highlight its impacts and present how our survey addresses an important gap in the occupational safety literature.

2. Background

The term "fatigue" is used to describe a number of different, sometimes interrelated, phenomena. Specifically, it may be used in referring 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, see Chaffin (1973) for a detailed description, (d) mental fatigue/exhaustion, defined by van der Linden et al. (2003) "as a change in psycho-physiological state due to sustained performance," and (e) symptoms associated with a number of medical ailments that include cancer, Parkinson's disease, depression and multiple sclerosis (Dittner et al., 2004; Shen et al., 2006). Based on the multidimensional nature of fatigue, there are no universal definitions for it (Shen et al., 2006; Cavuoto and Megahed, 2016). From a workplace perspective, fatigue is linked to an impaired/reduced performance (e.g., see the discussion in Brown, 1994; Dittner et al., 2004; Barker and Nussbaum, 2011; Yung, 2016; Yildiz et al., 2017, and Filtness and Naweed, 2017). Thus, in this paper, we use "fatigue" to denote "a lower level of strength, physical capacity, or performance as a result of work activities." We include "strength" and "physical capacity" in our definition since they are important to manufacturing tasks. Note that both "capacity" and "performance" were included in the definition of fatigue that came from the CRE-MSD Workshop, Toronto (see 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 (Björklund et al., 2000; Côté et al., 2005; Huysmans et al., 2010): discomfort, lowered strength, and reduced motor control. 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 result in 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) a 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).

Due to the negative consequences of fatigue, there has been a large number of studies that 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 have suffered from fatigue in the past 2-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) estimated that "90% of shift workers reported regular fatigue and sleepiness at the workplace." For estimates in specific industries, see Barker and Nussbaum (2011), Mehta et al. (2016), Yildiz et al. (2017) and Yoo et al. (2017). In our estimation, 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 paper, we survey U.S. manufacturing companies to assess the prevalence of fatigue, its drivers and how workers attempt to manage it.

Based on the discussion above, there are potentially two main differentiators across industries: (a) how fatigue affects public interests (i.e., consider the number of people who witness or get impacted by an instance of a fatigued employee in each of these domains), and (b) to some extent, 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.). Based on the discussion in Section 1, there are several indicators that these two differentiators are changing (at least in the US). First, the federal investments using taxpayer dollars reflect a significant shift in the public's interest in manufacturing operations (see Zients and Holdren, 2016). Second, the literature suggests that job duties, workload and task repetition have been altered by advanced manufacturing technologies (see Section 1); however, 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.

The remainder of this paper is organized as follows. Section 3 presents a detailed discussion of the survey design and data collection/analysis approaches. In Section 4, the results are provided and discussed. Some concluding remarks and future research ideas are provided in Section 5.

3. Methods

3.1. 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 (see Section 3.2 for details). 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, where we asked them to share the link to our survey to their employees; and (b) survey invitation emails that were sent through the membership list of several American Society of Safety Engineers (ASSE) listservs. 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.

3.2. Survey design and procedure

This survey was designed as a cross-sectional study, which aims to examine the three major questions listed in Section 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 (e.g., see 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/length of stay in this position, 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 analogue scales (VAS) due to the reasons mentioned in Section 2. 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 in other causes. Fifteen items were in 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/illness; 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 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 1 presents an overview of some of the 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;
(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.

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). The survey was created using the Qualtrics Survey Software. Data collection occurred between the mid of February to the beginning of May in 2016.

3.3. 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 was primarily used for the analysis for all four components. In the subsections below, we briefly discuss these four components.

3.3.1. Demographics of survey respondents and characteristics of their jobs

This component captures data categories (A)-(C) from Section 3.2. 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 the mean and standard deviation for any continuous variable, and percentages

Table 1
Differences between our survey and existing fatigue scales, questionnaires and surveys in the literature - adapted from Dittner et al. (2004).

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	Past 2 weeks	9	7-point Likert	No
GVA Monk (1989)	Mood	Severity	Psychiatric	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	Past month	40	5-point Likert	No
FSI Hann et al. (1998)	General	Severity, impact,duration	Cancer	Past week	14	11-point Likert	Yes
MFSI Stein et al. (1998)	Global, physical, mental, emotional	Phenomenology, severity	Cancer	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 patient	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 Paper	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 Analogue 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, FAS: Fatigue Assessment Scale, CFQ: Chalder Fatigue Scale.

were used to capture the frequency of a certain category being selected by the respondents.

3.3.2. *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 3.2). 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 paper, 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 0.891) and MFL could represent the worst case fatigue scenario.

Since we can use the VAS = 20 cut-off for the MFL to categorize our participants into fatigued and not-fatigued, we present summary statistics for the body parts affected for fatigued participants. 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.

3.3.3. *Main drivers of fatigue*

By focusing on those respondents who were deemed fatigued, there are two analyses can provide insights into the drivers of fatigue. First, we can evaluate their responses for: workers perceived causes of fatigue (i.e. Category (D) in Section 3.2). 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 only limit our analysis to 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:

$$Supp(A) = \frac{\text{Number of respondents who selected A}}{\text{Total number of fatigued respondents}}. \quad (1)$$

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:

$$Conf(A \rightarrow B) = \frac{E_A}{E_B} = \frac{\text{Number of respondents who selected A}}{\text{Number of respondents who selected B}}. \quad (2)$$

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 measured used to capture whether such a relationship is interesting or not. Lift (A → B) is > 1 if and only if the selection of A is increases the probability that B is also selected by the respondent. In this paper, we use SAS Enterprise Miner to perform the market basket analysis. We only report the results, which has $Supp \geq 0.10$, $Confidence \geq 0.5$, 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, increase the likelihood of another cause to be selected. The reader is referred to Han et al. (2011) and Leskovec et al. (2014) for more details on the Market Basket Analysis approach.

In the second analysis, we conduct a bivariate analysis between the reported individual characteristics and exposures (i.e. Categories (A)-(C) of Section 3.2) against the dichotomized "Most Fatigued 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. 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 1) or mean difference (does not contain 0).

3.3.4. Overview of individual coping measures

Similar to Section 3.3.3, the 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).

4. Results and discussion

4.1. Demographics of survey respondents and characteristics of their jobs

As of May 7^{th}, 2016 (≈ 2 months since our first survey invitation email was sent out), 807 individuals have accessed the online survey. The survey was completed by 451 individuals, i.e. a completion rate of 55.9%. The number of completed surveys exceeded our target of 385 completed surveys, which means that the margin of error for the survey is at most 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 provides a summary of the respondents' demographics and their fatigue-related individual characteristics. Note that these correspond to Categories (A) and (B) of Section 3.2.

Table 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 thifee lowest 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). We define the level of fatigue impact of work as "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 h, 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 h (Bureau of Labor Statistics, 2016).

4.2. The prevalence of fatigue among manufacturing workers

4.2.1. The overall prevalence of fatigue

In Section 4.1, the descriptive statistics for the survey data were provided. Here, 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.

As mentioned in Section 3.3.2, 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 Fatigue Level", 260 workers (out of 451 respondents) are 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%. The reader should note that 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 over the past week. In our estimation, this relatively large number can be potentially explained by a number of different factors. First, the transition to advanced manufacturing environments have resulted in increased workloads and job responsibilities on manufacturing workers (as highlighted in Section 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) present 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.

Table 2
The demographics of respondents and their fatigue-related individual characteristics ($n = 451$). The mean and standard deviation (SD) are reported for continuous variables, while percentages (%) are reported for categorical variables.

(A) Demographics of the respondents			(B) Fatigue-related individual characteristics		
Variable	Mean (SD)	%	Variable	Mean (SD)	%
Age (yr)	48.3 (10.1)	–	*Cigarette Use*		
Sex			No	–	92.5
Male	–	82	Yes	–	7.5
Female	–	18	*Alcohol Use*		
Height (ft)	5.8 (0.3)	–	0-1 units per week	–	52.5
Weight (lb)	210.2 (40.9)	–	1-2 units per week	–	12
Body Mass Index	30.3 (5.3)	–	3-6 units per week	–	20
(BMI) (kg/m^2)			7-9 units per week	–	6.7
Obesity Categories			>9 units per week	–	8.9
Normal Weight	–	12.4	*Exercise Level*		
($18.5 < BMI \leq 25kg/m^2$)			Seldom	–	30.4
Overweight	–	41.2	1 time per month	–	3.8
($25 < BMI \leq 30kg/m^2$)			1 time per week	–	18
Obese	–	46.3	3 times per week	–	32.6
(BMI $> 30kg/m^2$)			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)	–

Table 3
Summary statistics for work related exposures and outcomes.

(C) Work-related exposures			(D) Fatigue outcomes	
Variable	Mean (SD)	%	Variable	Mean (SD)
Repetitive Processing or Assembly	19.0 (31.1)	–	Fatigue Frequency Level (FFL)	36.9 (31.8)
Equipment Operation	22.4 (34.6)	–	Most Fatigued Level (MFL)	44.8 (36.4)
Overhead Work	12.6 (20.4)	–	Fatigue Impact at Work (FIW)	22.4 (26.0)
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		

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.

4.2.2. *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 (based on the literature, see Section 3.2) 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 Fig. 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 could indicate these body parts are impacted more often for our fatigued participants.

The VAS values for the body locations can be justified by the survey responses and literature. For the sake of conciseness, 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 h/workday on average from Table 3) when compared to sitting and standing can justify 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). Besides, the back was often reported as the frequently injured part of body for nonfatal injuries and illnesses among manufacturing industry (see https://www.bls.gov/news.release/pdf/osh2.pdf). 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).

Per Section 3.3, 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

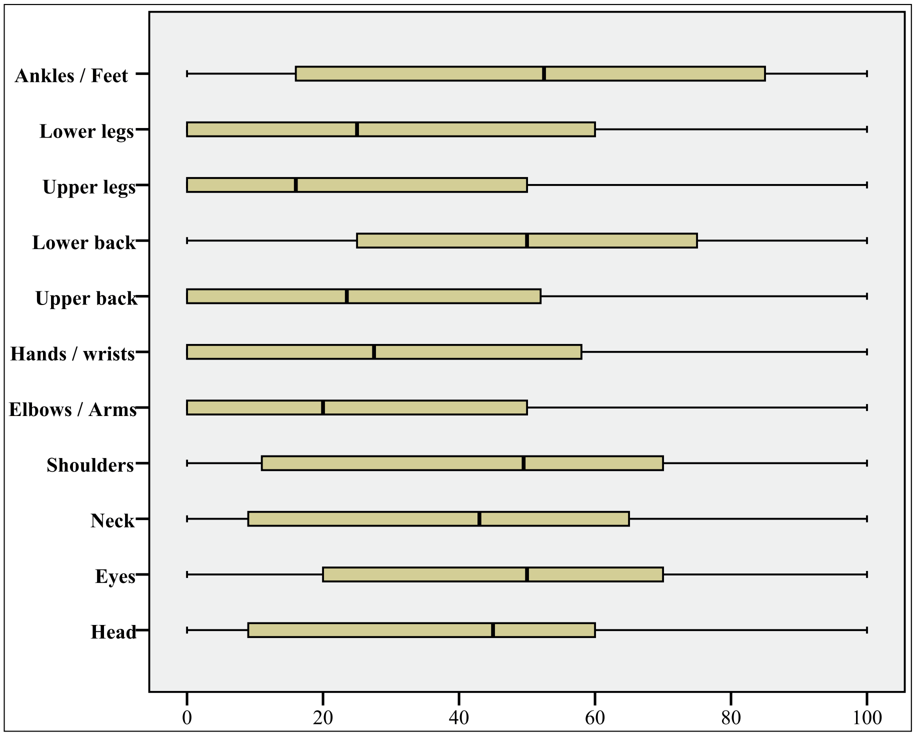

Fig. 1. Frequency of body locations affected for fatigued workers.

counterparts. The statistically significant mean difference 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 and 3.3.

4.3. *Main drivers of fatigue*

4.3.1. *Perceived root causes for fatigue*

We present the percentage of fatigued participants who selected each root-cause in Fig. 2. The top three 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.

In addition to the percentage of each single voted 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 Fig. 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 4 (with the inclusion criteria detailed in Section 3.3.3).

The results of Table 4 are explained as follows. Let us consider 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 Fig. 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 more likely when shift schedule and lots of movement are selected together when compared to it being selected at random. The aforementioned logic can be applied to any row in Table 4. In general, the relationships in the table has a support of at least 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.

4.3.2. *Bivariate analysis between exposures and fatigue*

To identify fatigue-related risk factors, we conducted a bivariate analysis between dichotomized fatigue outcomes and several of the measured variables. Table 5 presents the factors that were found to be significantly associated with this fatigue.

Among the variables relating to demographics and individual fatigue related factors, 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%). These results indicate that fatigued workers have a higher larger odds of being older. This is in accord with the findings among CNC Lathe operators where age and length of stay 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 in 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%), and fewer fatigued workers worked in rotated shift

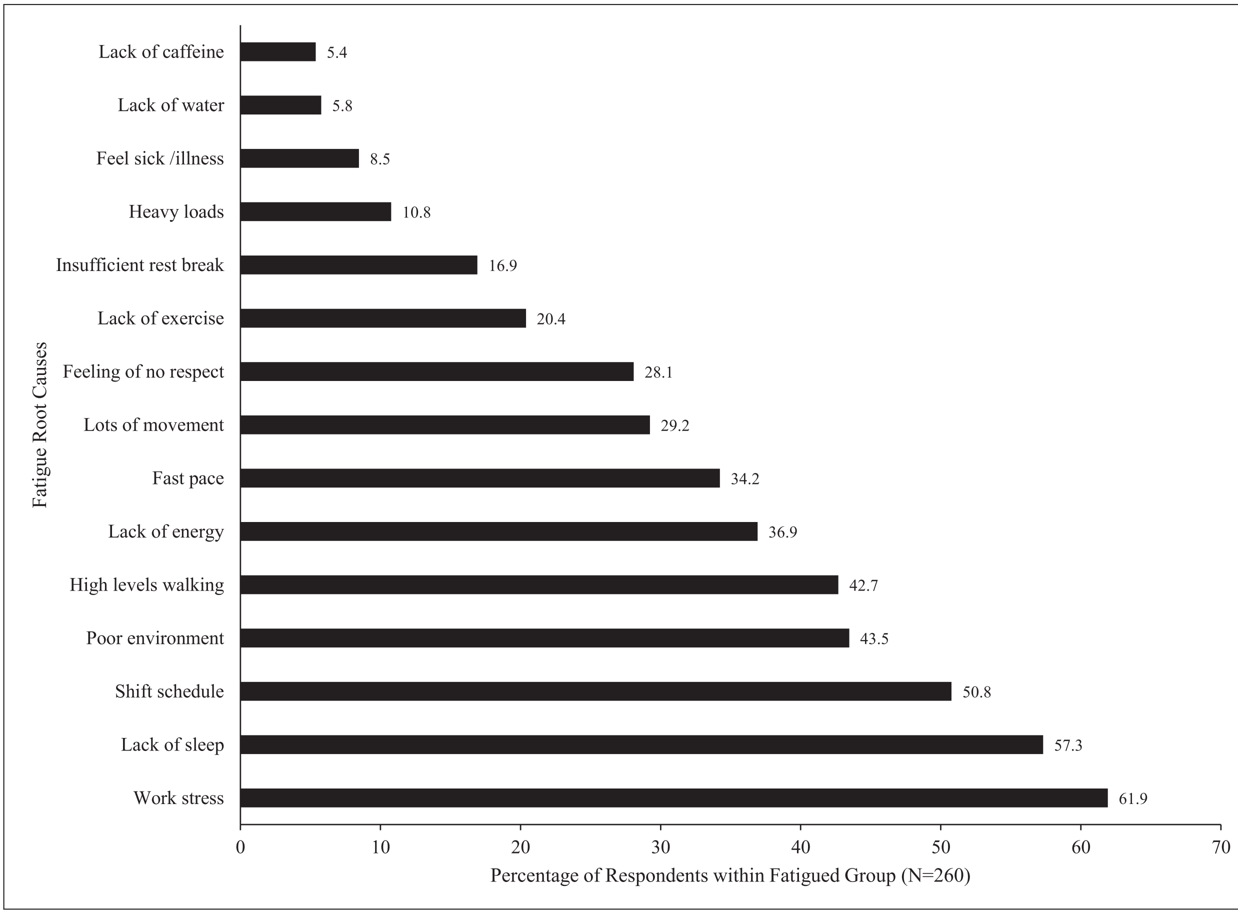

Fig. 2. Percentage of fatigued respondents selecting a root-cause.

Table 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

schedules (54.0%) compared with not-fatigued workers (71.1%). As the effect of alcohol use was frequently reported to interfere with worker circadian rhythms and subsequently affects sleep quality and lead to fatigue with decreased work performance (Dawson and Reid, 1997), the positive association between alcohol use and fatigue is consistent with our expectations. The negative association between rotated shift work and fatigue was counterintuitive at first sight as rotated 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). Besides, by cross tabulating between the frequency of conducting job tasks and the rotate shifts indicator, we found that rotated 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 percent 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 rotated shifts, they also spent more time in the demanding work tasks, which could have a more dominant positive association with fatigue than rotate shifts.

On average, fatigued workers spent more time 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). As the literature suggested, 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 4.1 and bivariate results above were also in accord with the three top causes (lack of sleep, work

Table 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)	0.965 (0.534, 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 (0.805, 3.991)
>9 units	8.9	7.9 (37.5)	9.6 (62.5)	1.493 (0.750, 2.974)
Length of time 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 (0.787, 7.870)
1–5 years	33.7	34.7 (43.4)	33.0 (56.6)	2.085 (0.889, 4.891)
5–10 years	14.4	14.2 (41.5)	14.6 (58.5)	2.252 (0.887, 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)	-0.319 (−0.520, −0.118)
Work hours per week	50.8 (10.1)	52.0 (11.2)	50.0 (9.1)	1.987 (0.103, 3.870)
Rotate shift				
No	38.8	28.9 (31.4)	46.0 (68.6)	0.366 (0.241, 0.555)
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)

stress and shift schedule) reported in Sec 4.3.1. First, 65.2% of workers reported sleeping less than 7 h (with 62.1% respondents sleeping 6 or less hours), and 86.7% of respondents worked more than 40 h during a typical work week (with 25% of respondents working 55 h 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 are important here. Second, work demands are one of the most common sources

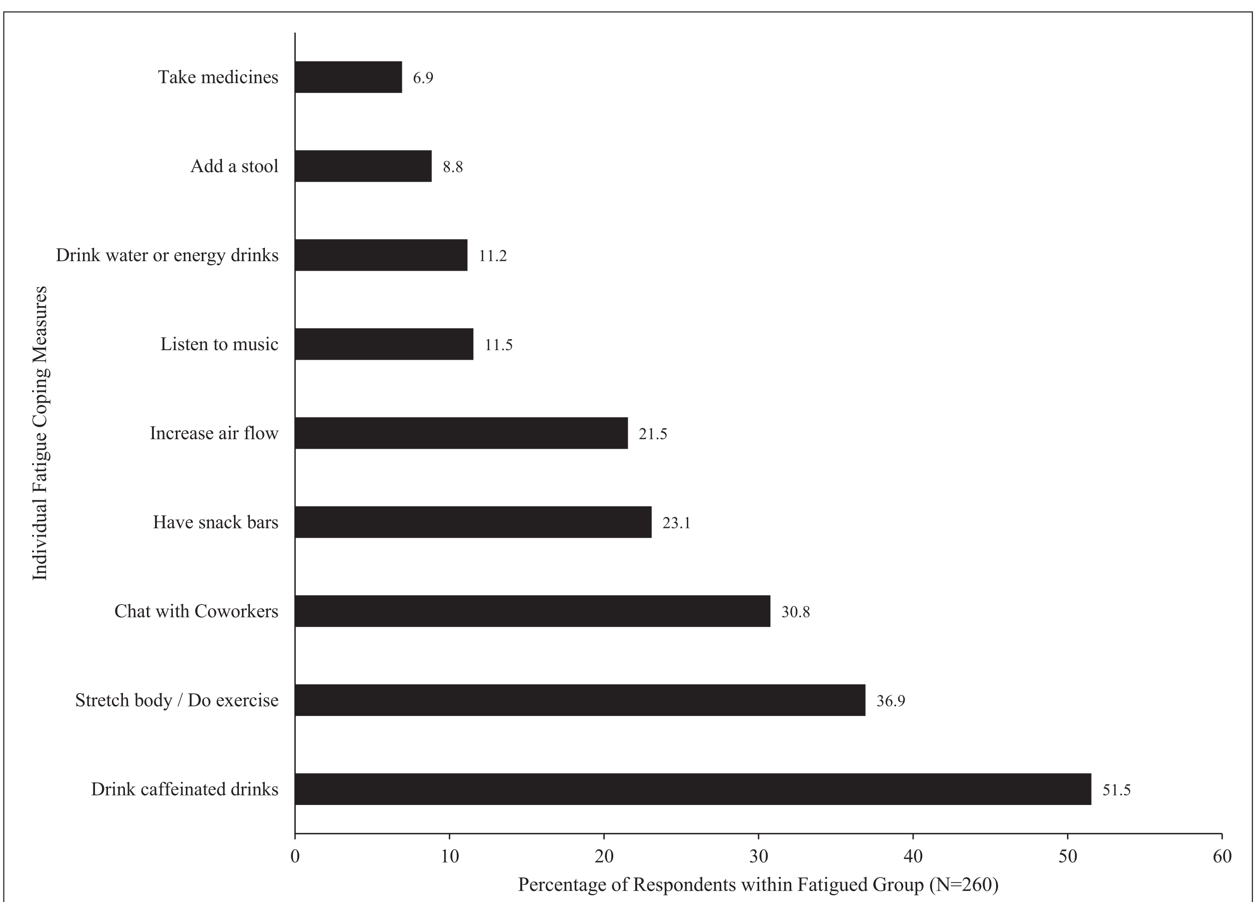

Fig. 3. Percentage of respondents selecting a recovery.

Table 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

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). In our bivariate analysis, the result that fatigued workers were found to spend more time in the five work tasks support the work stress as the second highest fatigue root cause. The fixed shift work was positively associated with fatigue when compared with rotated 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.

4.4. Overview of individual coping measures

The results from the survey provide some insights on individual coping measures for fatigued respondents. From Fig. 3, the bar chart shows the top three adopted recovery methods would be: 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).

The Market Basket Analysis for capturing the frequent combinations of individual coping measures is summarized in Table 6. Similar to Section 4.3, we only include the results where the support, confidence and lift are greater than 15%, 50%, and 1, respectively. From Table 6, 20% of fatigued workers tend to both chat with coworkers and drink caffeinated drinks as coping mechanisms to combat fatigue. 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.

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 relate to fatigue management, and (d) availability of health/fitness programs and/or stress management classes to 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 mining and transportation industries (see Cavuoto and Megahed, 2016 for more details).

5. Conclusions

This paper 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.

5.1. Limitations and Future Directions

While the results of this study are significant, there are limitations that must be acknowledged. The cross-sectional nature of the survey design limits the ability to discern the direction of observed associations. Causal relationships cannot be definitively 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.

5.2. Strengths and implications

The reader should note that the motivation and scope of this survey is 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 expanded to healthy subjects later (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). In our estimation, the use of fatigue scales in medical practice allows for having 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 it is anonymized. Thus, we had to limit the number of questions for each construct (based on the feedback from several practitioners). 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) we 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 (which can be justified by the findings in Broderick et al., 2008). Third, there are no 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 (see Broderick et al., 2008 for more details).

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 parts when workers feel fatigued include ankles/feet, lower back, and eyes. Shoulders, head and neck are also top rated for fatigue frequency. Fatigue presence was associated with age, alcohol use, experience, hours of sleep, work hours per week, rotate 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 error. 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.

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Supplementary materials

Supplementary documents are available online (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.

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