Understanding fatigue and the implications for worker safety

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Introduction

Workplace safety requires a systematic approach that includes an understanding of risk factors and identification of hazards. Worker fatigue has been identified as a risk factor for both acute and cumulative injuries. Fatigue and incomplete recovery can lead to decreased capacity that can result in an increased risk of injury and a decline in work efficiency (Kumar 2001, de Looze, Bosch, and van Dieën 2009, Visser and van Dieën 2006). In addition, fatigue contributes to accidents, injuries and death (Williamson et al. 2011). Over $300 million in lost productivity time in US workplaces can be tied to fatigue. Significantly reducing the incidence of fatigue-induced workplace injuries and lost productivity depends on the accurate and timely detection of fatigue to allow for appropriate intervention.

Although the term fatigue is commonly used, it has come to refer to many concepts in occupational safety and health. In order to manage and mitigate fatigue and the associated risks, it is essential to understand the different types and components. Fatigue is generally accepted as resulting in the impairment of capacity or performance as a result of work. However, fatigue is multidimensional, either acute or chronic, whole body or muscle level, physical or mental, central or peripheral. In addition, it includes a decline in objective performance, as well as perceptions of fatigue. Of added importance are the roles of sleep and circadian function. Each of these aspects of fatigue do not occur in isolation, but interact to modify worker capacity and injury risk. Both mental and physical fatigue can result in poor decision making, which may result in an acute injury (Williamson et al. 2011). The risk of injury is dependent on both the injury mechanism and the characteristics of the work being performed. Parameters of importance in the development of fatigue, and subsequent risk, include the length of time-on-task between breaks, work pace, and the timing of rest breaks (Williamson et al. 2011).

Researchers have postulated that through delineation of the quantitative details of relevant variables, appropriate interventions and injury control can be developed (Kumar 2001). How to best quantify workplace conditions, particularly physical exposures experienced by the worker, remains an open research question (Kim and Nussbaum 2012). Current approaches to fatigue monitoring and detection often rely either on fitness-for-duty tests to determine whether the worker has sufficient capacity prior to start work, monitoring of sleep habits, or intrusive monitoring of brain activation (using electroencephalography (EEG)) (Balkin et al. 2011) or changes in local muscle fatigue (using electromyography (EMG)) (Dong, Ugaldey, and El Saddik 2014). While there is no single standard measurement of fatigue, there are numerous subjective measurement scales and objective measurement techniques that can be adapted for workplace use. Recent advances in wearable technologies also present an opportunity for real-time and in-the-field assessment of fatigue development.

Why should we care about fatigue?

Fatigue in the workplace is often described as a multidimensional process, which results in a diminishing of worker performance. It results from prolonged activity, and is associated with psychological, socioeconomic and environmental factors (Barker and Nussbaum 2011, Yung 2016). From an occupational health and safety perspective, fatigue must be managed and controlled since it has significant short-term and long-term implications. In the short-term, fatigue can result in discomfort, diminished motor control, and reduced strength capacity (Björklund et al. 2000, Côté et al. 2005, Huysmans et al. 2010). These effects might lead to reduced performance, lowered productivity, deficits in work quality, and increased incidence of accidents and human errors (Yung 2016). Fatigue can also result in longer term adverse health outcomes, including, e. g., chronic fatigue syndrome (Yung 2016) and reduced immune function (Kajimoto 2008). It can be seen as a precursor to work-related musculoskeletal disorders (WMSDs) (Iridiastadi and Nussbaum 2006). “ These outcomes have been associated with future morbidity and mortality, work disability, occupational accidents, increased absenteeism, increased presenteeism, unemployment, reduced quality of life, and disruptive effects on social relationships and activities” (Yung 2016).

The safety impacts of fatigue are best evidenced in the transportation domain. In the U. S., an estimated 32, 675 people died in motor vehicle crashes in 2014 (2015a). In 2013 there were 342, 000 reported truck crashes that resulted in 3, 964 fatalities and ~95, 000 injuries (2015b). While these crashes often result from several factors, it is estimated that driver-related factors are the leading cause for 75-90% of fatal/injury-inducing crashes (Craye et al. 2015, Stanton and Salmon 2009, Medina et al. 2004, Lal and Craig 2001). The National Highway Traffic Safety Administration (NHTSA) estimates that about 20% of all crashes are fatigue-related (Strohl et al. 1998) and 60% of fatal truck crashes can be attributed to the driver falling asleep while driving (Craye et al. 2015). Drowsy driving increases crash risk by 600% over normal driving (Klauer et al. 2006).

For many years, a succinct definition of fatigue has been sought after (Aaronson et al. 1999). In our estimation, there is no simple and standard definition for fatigue. For example, our statement above: *Fatigue in the workplace is often described as a multidimensional process, which results in a diminishing of worker performance* , while true, is not sufficient to describe fatigue, since there are many other conditions that may result in a diminished worker's performance (e. g., motivation). Perhaps, more importantly, there are several other factors that impact our ability to determine one standard definition:

1. Workplace fatigue development mechanisms differ significantly according to the occupation type. For example, in manufacturing, the focus is typically on physical/muscle fatigue or related to the shift schedule, and in transportation drowsiness and sleepiness are often the root-causes for driver fatigue.
2. Given the complexity of the human body, a single mechanism unlikely explains fatigue under all conditions, even for a single task and fatigue type (i. e. muscle fatigue) (Weir et al. 2006).
3. No one definition can explain the complex interactions between biological processes, behavior, and psychological phenomena (Aaronson et al. 1999).
4. It is unlikely that a single theory can be used to explain all observations of performance deterioration (Weir et al. 2006).

Thus, we cannot provide a single definition of fatigue in this paper. Instead we refer the reader to Yung (2016, p. 14) for a summary of multiple example fatigue definitions from various domains.

Measuring and Quantifying Fatigue

In this section, we divide how fatigue is measured according to cognitive and physical functions respectively.

Talk about PVT and reaction time as the main standards for sleep-related fatigue

There are several important cognitive characteristics that are typically assed in the context of fatigue. These include: a) arousal, b) alertness/ attention, c) cognitive control, d) motivation, and e) stress. Arousal is commonly measured in transportation safety studies since it aims at assessing sleep deprivation, an important root-cause for trucking crashes (especially at night) (Philip et al. 2005, Strohl et al. 1998). Measures of arousal include heart rate, electrodermal response (EDR), pupil dilation and self-report questionnaires (Yung 2016). Alertness and attention are important in translating sensory and work-related inputs into actionable items. They can be measured using gaze direction, EEG, validated scales, and questionnaires. The third characteristic, cognitive control, has to do with the time taken to process information, and thus, reaction time is perhaps the most commonly used measure for evaluating it. The fourth characteristic is perhaps the hardest to measure since motivation cannot be assessed except through questionnaires and validated scales. Stress can be assessed through a number of measures which include heart rate variability, blood pressure and body postures (Yung 2016). The reader should note that the measures for quantifying mental fatigue include intrusive monitoring systems (e. g. EEG and blood pressure monitoring systems), non-intrusive measures (camera systems to detect gaze direction), and somewhat subjective measures (questionnaires and scales). Table 1 provides a summary of physiological and physical indicators of fatigue.

Table 1: Typical Physiological and Physical Indicators of Fatigue Development

Measurement	Direction of Change with Fatigue
Heart rate	Increases with physical fatigue
Heart rate variability	Decreases with mental fatigue (for root-mean square of the successive

	differences (RMSSD))
Increased Low Frequency / High Frequency (LF/HF) power ratio	
Electromyography	Decrease in mean power frequency Increase in root mean square amplitude
Strength	Decrease in maximum exertion
Tremor	Increase in physiological and

	postural tremor
Pupil dilation	Increases with mental fatigue and drowsiness
Blink rate	Increased percentage eyelid closure over the pupil, over time (PERCLOS)
Reaction time	Increased reaction time and lapses (using psychomotor or vigilance

	task (PVT))
Performance	Increase in errors and task completion time
Force variability	Increase in variability with physical fatigue
Subjective assessment	Increase in ratings of discomfort and fatigue

On the physical side, electromyography is one of the most commonly used evaluation tools for muscle fatigue in a laboratory setting. The gold standard is to detect cellular and metabolic changes through blood sampling techniques (Garde, Hansen, and Jensen 2003). Since these approaches are intrusive, some researchers attempt to detect symptoms of physical fatigue. These symptoms include an impairment in postural control (Davidson, Madigan, and Nussbaum 2004), increased sway (Davidson, Madigan, and

Nussbaum 2004), and joint angle variability (Madigan, Davidson, and Nussbaum 2006). Additional symptoms include an increase in exerted force variability (Svendson et al. 2010) and increased tremor (Lippold 1981). Note that these symptoms can be observed through the use of check sheets, visual inspection (manual and/or through cameras), and self-reported questionnaires among other tools.

In our estimation, most methods described above are of limited use in practice since they are either invasive (and will be resisted by individuals/unions) or rely on visual inspection performed by an observer. Perhaps, more importantly, each observational and measurement technique also focuses primarily on one main risk factor, such as posture or force, or a combined set of factors but for a repetitive task, such as the NIOSH work practices guide (Waters et al. 1993). This fails to capture the interactive nature of many fatigue precursors as well as the variability of the work performed. In addition, these methods do not take into account the characteristics of the individual, beyond general anthropometric and demographic attributes, such as height and age. One important consideration is that the application of these methods in field studies and practice have also been limited by the question: “ can we detect if fatigue (or its symptoms) has occurred?” Note that this question is binary with a yes/no answer. However, it is well understood that fatigue is a process that occurs as a function of loading, time and exertion and is not an end point.

From a safety perspective, a more interesting question is: “ Can we predict when fatigue will occur for a given worker based on their schedule, environment and job tasks?” If this can be done, then fatigue management will progress from a reactive state (equivalent of the personal protective equipment state in traditional hazard control theory) to higher/safer levels of engineering controls, substitution and/or perhaps elimination through modeling and scheduling. The increasing availability of pervasive sensing technologies, including wearable devices, combined with the digitization of health information has the potential to provide the necessary monitoring, recording, and communication of individuals' physical and environmental exposures to address this question (Kim and Nussbaum 2012, Vignais et al. 2013). In the following section, we describe some of the research and commercially available products that are used for predicting/monitoring fatigue development.

Predicting Fatigue Development

Models for fatigue development are not new, but the existing models are often incomplete. Models for predicting/understanding how humans fatigue have received significant attention over the past few decades in the fields of aviation, driving, mining, and professional athletics.

In the transportation areas (i. e. aviation and driving), the models originated from efforts to model the underlying relationships between sleep regulation and circadian dynamics (Dinges 2004). Dinges (2004) present a survey of the biomathematical models used in this area. There are also some surveys on driver fatigue detection models, see e. g. Wang et al. (2006). However, based on our interactions with one of the larger trucking companies in the U. S., these models do not offer answers to the following question: " Given the massive data collected on each truck that include indirect indicators of fatigue, e. g. lane departures and hard brakes, and individual characteristics of each driver, can we predict how each driver will fatigue for a given assignment, traffic condition and weather profile?” With the advent of *big data* , this is the direction that is needed for fatigue development in the trucking industry. One can make parallels for aviation and military applications.

In mining, there are commercially available products that *claim* to predict fatigue among mine workers. The authors did not have the chance to test these products and thus, we cannot verify/validate these claims. However, if true, this system will be a significant contribution to mining safety.

Based on the above discussion, there are several important observations to be made. First, there has not been much independent research verifying the claims made for any commercial products. Thus, practitioners should use them with caution and in tandem with their current safety methods. Second, there have been only limited attempts to perform inter-disciplinary research in fatigue development. Thus, the current approaches are domain-dependent and are often incomplete since they consider only a few precursors. There needs to be a systematic move towards utilizing *big data analytics* as a mechanism to harness the massive amounts of data that is being captured on our equipment, workers, etc. The research challenge is to ensure that we are asking the right questions prior to considering what the technology can (or cannot) provide. Third, it is somewhat inexplicable that the manufacturing safety community is significantly behind other safety domains. We believe that there is a significant opportunity for both researchers and practitioners in examining how other disciplines are managing fatigue.

General Strategies for Fatigue Management and Mitigation

There are several somewhat recent publications that detail how to manage physical and/or mental fatigue indicators (Hartley and Commission 2000, Caldwell, Caldwell, and Schmidt 2008, Williamson et al. 2011, Williamson and Friswell 2013). These studies have presented the typical hazard control recommendations, which include administrative and engineering controls that can reduce/mitigate the development of fatigue. Practitioners should also consult the documentation from Transport Canada on *Developing and Implementing a Fatigue Risk Management System* (https://www. tc. gc. ca/media/documents/ca-standards/14575e. pdf). Typical interventions include: rest (for physical fatigue), sleep (for alertness), modified work-rest schedules, and limits on the cumulative hours worked in a week (or shift changes). While these strategies are effective for population averages/overall, they do not address the weakest link in the workforce (i. e. those most likely to fatigue and/or get injured). We see much work needed in this area.

Concluding Remarks

In this paper, we have provided an overview of some of the current issues in fatigue detection/ management research and practice. Based on our review of the literature, we offer the following advice to safety professionals:

1. Transportation Safety Professionals : There is a significant body of research that highlights the impact of lack of sleep (e. g. from sleep apnea and/or scheduling), night driving, weather (e. g. cloudy or rainy), and work-rest schedules on fatigue development. In general, less sleep, night driving, bad weather and frequent changes in the work-rest schedule are more detrimental to transportation safety. To mitigate these risks, the routing/scheduling can be modified to alleviate some of these precursors. In addition, wearable sensors and on-vehicle systems (e. g. lane departure and hard brake detection sensors) can provide real-time indicators of fatigue development in driving. The data from these sensors can be used through simple dashboards that provide the dispatcher with information on which drivers are at risk. The dispatcher can then force these drivers to rest if fatigued (and sleep in-cabin at a truck stop if necessary) since a short break/nap can help mitigate these effects.
2. Manufacturing Safety Professionals : Fatigue has been shown to be a precursor to risky behaviors and long-term injuries. It is also associated with a diminished performance and, therefore, can result in significant quality problems. Based on our discussion with several safety managers from large automotive companies, we have learned that it is often easier to “ sell” safety projects to upper management when it is combined with quality improvement initiatives. The rationale is simple to management since they can see a return on investment (ROI) on these projects when compared to a softer objective (reducing/eliminating the probability of a safety problem that has not occurred before). In addition, we challenge practitioners to categorize

their at-risk populations (e. g. unexperienced workers, obese and/or elder workers, etc.). These workers cannot be modeled by existing ergonomics and safety models that consider an *average* worker. Thus, a dashboard and sensors that monitor their absenteeism, quality of their work and/or complaints can be used to trigger appropriate interventions.

3. Mining Safety Researchers: The technology with fatigue monitoring (and more general safety) in mining has evolved significantly over the past decade. There are several commercial products that allow for active monitoring, scheduling, and equipment safety checks. To our knowledge, at least one major equipment manufacturer has released a safety systems suite that incorporates all these data sources to present a clear picture of a worker's fatigue and distraction risk. We did not test the validity of these claims and therefore, we ask safety practitioners to ask for system demos and ensure that this particular system meets their needs.

A word of caution: fatigue detection systems do not mitigate and/or eliminate fatigue. In addition, we urge safety professionals to embrace the role of technology and its potential to redefine safety from a one system fits all to an individualized approach.

For researchers and educators , we believe that there is a sufficient body of literature that suggests that our community is headed to individualized safety models. To develop these models, there needs to be an emphasis on managing large amounts of data, revisiting our old models and ensuring that we can offer data-driven interventions for safety/ergonomics problems. In essence, our field is moving towards individualized models and evidence-based interventions.

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