

Understanding Fatigue Implications for Worker Safety

By Lora Cavuoto and Fadel Megahed

Workplace safety requires a systematic approach that includes an understanding of risk factors and hazards. Worker fatigue is a risk factor for both acute and cumulative injuries. Fatigue and incomplete recovery can lead to decreased capacity that can increase risk of injury and degrade work efficiency (de Looze, Bosch & van Dieën, 2009; Kumar, 2001; Visser & van Dieën, 2006). Also, fatigue contributes to incidents, injuries and fatalities (Williamson, Lombardi, Folkard, et al., 2011).

In U.S. workplaces, fatigue is associated with more than \$300 million in lost productivity time. Reducing the incidence of fatigue-induced workplace injuries and lost productivity depends on the accurate and timely detection of fatigue to allow for an appropriate intervention.

Although the term *fatigue* is commonly used, it has come to encompass many concepts. To manage and mitigate fatigue and the associated risks, one must understand the different types of fatigue and components.

Fatigue as a result of work impairs a person's capacity or performance. 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.

The roles of sleep and circadian function are also important considerations. These aspects of fatigue do not occur in isolation; rather they 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 suggest that by delineating the quantitative details of relevant variables, stakeholders can develop appropriate interventions and injury controls (Kumar, 2001). How to best quantify workplace conditions, particu-

larly physical exposures experienced by the worker, remains an open research question (Kim & 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 before starting work, monitoring of sleep habits, or intrusive monitoring of brain activation [using electroencephalography (EEG)] (Balkin, Horrey, Graeber, et al., 2011) or changes in local muscle fatigue [using electromyography (EMG)] (Dong, Ugaldey & El Saddik, 2014).

While there is no single standard measurement of fatigue, OSH professionals can adapt numerous subjective measurement scales and objective measurement techniques for workplace use. Recent advances in wearable technology also present an opportunity for real-time and in-the-field assessment of fatigue development.

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Why Should We Care About Fatigue?

Fatigue in the workplace is a multidimensional process that results in diminished worker performance. Fatigue results from prolonged activity and is associated with psychological, socioeconomic and environmental factors (Barker & Nussbaum, 2011; Yung, 2016).

In the short term, fatigue can result in discomfort, diminished motor control and reduced strength capacity (Björklund, Crenshaw, Djupsjöbacka, et al., 2000; Côté, Raymond, Mathieu, et al., 2005; Huysmans, Hoozemans, van der Beek, et al., 2010). In the longer term, these effects might lead to reduced performance, lower productivity, poor work quality, and increased rates of incidents and human error (Yung, 2016). Fatigue can also be seen as a precursor to work-related musculoskeletal disorders (Iridiastadi & Nussbaum, 2006; Kumar, 2001).

The safety implications of fatigue are best evidenced in the transportation domain. In the U.S., motor vehicle

crashes resulted in nearly 32,700 fatalities in 2014 (NHTSA, 2015a). In addition, 342,000 reported truck crashes resulted in 3,964 fatalities and approximately 95,000 injuries (NHTSA, 2015b). While these crashes have several causal factors, estimates indicate that driver-related factors are the leading cause of 75% to 90% of fatal/injury-inducing crashes (Craye, Rashwan, Kamel, et al., 2015; Lal & Craig, 2001; Medina, Lee, Wierwille, et al., 2004; Stanton & Salmon, 2009).

National Highway Traffic Safety Administration (NHTSA) estimates that 20% of all crashes are fatigue-related (Strohl, Merritt, Blatt et al., 1998) and 60% of fatal truck crashes can be attributed to the driver falling asleep while operating the vehicle (Craye, et al., 2015). Drowsy driving increases crash risk by 600% over normal driving (Klauer, Dingus, Neale, et al., 2006).

Researchers have long attempted to succinctly define *fatigue* (Aaronson, Teel, Cassmeyer, et al., 1999), but there is no simple and standard definition. For example, the earlier statement, "Fatigue is often described as a multidimensional process that results in diminished worker performance," is true, yet it does not sufficiently describe fatigue, since many other conditions (e.g., motivation) may result in diminished performance.

Furthermore, several other factors affect the ability to develop a universal definition:

1) Fatigue development mechanisms differ significantly according to occupation type. For example, in manufacturing, the focus is typically on physical/muscle fatigue or shift schedule; in transportation, drowsiness and sleepiness are often the root causes for driver fatigue.

2) Given the complexity of the human body, a single mechanism is not likely to explain fatigue under all conditions, even for a single task and fatigue type (e.g., muscle fatigue) (Weir, Beck, Cramer, et al., 2006).

3) No single 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 explain all performance deterioration (Weir, et al., 2006).

Given this, readers are encouraged to review Yung (2016, p. 14) for a summary of multiple fatigue definitions from various domains.

Measuring & Quantifying Fatigue

Several important cognitive characteristics are typically measured in the context of fatigue. These include: a) arousal; b) alertness/attention; c) cognitive control; d) motivation; and e) stress (Yung, 2016). Arousal is commonly measured in transportation safety studies since it aims to assess sleep deprivation, an important root cause of trucking crashes (especially at night) (Philip, Sagaspe, Moore, et al., 2005; Strohl, et al., 1998). Measures of arousal include heart rate, electrodermal response, pupil dilation and self-reported 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, involves the time taken to process information; thus, reaction time (assessed using the psychomotor vigilance task) is perhaps the most commonly used measure for evaluating cognitive control.

Motivation is perhaps the most dif-

ficult fatigue characteristic to measure since one cannot assess it except through questionnaires and validated scales. Stress can be assessed through several measures, including heart rate variability, blood pressure and body postures (Yung, 2016).

Readers should note that the measures for quantifying mental fatigue include intrusive monitoring systems (e.g., EEG, blood pressure monitoring systems), nonintrusive measures (e.g., camera systems to detect gaze direction) and somewhat subjective measures (e.g., questionnaires and scales). Table 1 summarizes commonly used physiological and physical indicators of fatigue.

On the physical side, due to the intrusive nature of detecting the chemical changes in the muscle, researchers attempt to detect symptoms of physical fatigue. EMG is commonly used to evaluate muscle fatigue in a laboratory setting. These symptoms include impaired postural control (Davidson, Madigan & Nussbaum, 2004), increased exerted force variability (Svendson & Madeleine, 2010), and increased muscle or body segment tremor (Lippold, 1981).

In advanced fatigue cases, one can observe these symptoms using check sheets, visual inspection (manual and

through cameras) and self-reported questionnaires, but these cases often require more advanced direct measurement tools. In a recent survey of manufacturing workers, respondents indicated a change in work postures and sweating, and a slowing of work pace as the most common symptoms of physical fatigue (Lu, Megahed, Sesek, et al., 2017).

Most of the methods described are of limited use in practice since they are either invasive (and will be resisted by individuals) or rely on visual inspection by an observer. Furthermore, each observational and measurement technique focuses primarily on one main risk factor, such as posture or force, or a combined set of factors for a repetitive task, such as the NIOSH work practices guide (Waters, Putz-Anderson, Garg, et al., 1993). These methods fail to capture the interactive nature of many fatigue precursors, as well as the variability of the work performed. In addition, these methods do not account for characteristics of the individual, beyond general anthropometric and demographic attributes (e.g., height, age).

In addition, application of these methods in field studies and practice has been limited to the question, Can we detect whether 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; it 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 his/her schedule, environment and job tasks? If so, then fatigue management can progress from a reactive state (the equivalent of the PPE state in a traditional hazard control hierarchy) to higher/safer levels of engineering controls, substitution and 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 & Nussbaum, 2012; Maman, Yazdi, Cavuoto, et al., 2017; Vignais, Miezal, Bleser, et al., 2013).

TABLE 1
Indicators of Fatigue Development

Measurement	Direction of change with fatigue
Heart rate	•Increases with physical fatigue
Heart rate variability	•Decrease in root-mean-square of the successive differences with mental fatigue •Increase in low frequency/high frequency 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	•Increase in percentage eyelid closure over the pupil over time
Reaction time	•Increased reaction time and lapses
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

Predicting Fatigue Development

Models for predicting/understanding how people fatigue have received significant attention over the past few decades in the fields of aviation, driving, mining and professional athletics. The models aim to characterize the underlying relationships between sleep regulation and circadian dynamics (Dinges, 2004).

Dinges (2004) presents a survey of the biomathematical models used in the transportation domain. Other surveys address driver fatigue detection models (e.g., Wang, Yang, Ren, et al., 2006). However, these models often do not offer answers to specific individual worker questions such as, Given the massive data collected on each truck (e.g., lane departures, 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 needed for fatigue management in the trucking industry. One can draw parallels for aviation and military applications as well.

In mining, some commercially available products claim to predict fatigue among mine workers. The authors have not tested these products and, thus, cannot verify/validate these claims. However, if true, these systems will be a significant contribution to mining safety.

Given these facts, consider several important observations.

1) Independent research verifying the claims made for any commercial products is limited. Thus, practitioners should use these products with caution and in tandem with their current safety methods.

2) Attempts to perform interdisciplinary research in fatigue development are limited. Thus, the current approaches are domain dependent and are often incomplete since they consider only a few precursors. The field needs to make a systematic move toward utilizing big data analytics as a mechanism to harness the massive amount of data being captured on equipment, workers and related components. The challenge is to ensure that the right questions are asked before considering what the technology can or cannot provide.

3) The manufacturing safety community is significantly behind other safety domains. This presents a significant opportunity for both researchers and

practitioners in examining how other disciplines are managing fatigue.

General Strategies for Fatigue Management & Mitigation

Several somewhat recent publications detail how to manage physical and/or mental fatigue indicators (Caldwell, Caldwell & Schmidt, 2008; Hartley & Commission, 2000; Williamson & Friswell, 2013; Williamson, et al., 2011). These studies have presented the typical hazard control recommendations, including administrative and engineering controls that can reduce/mitigate the development of fatigue. Practitioners should also consult Transport Canada's Developing and Implementing a Fatigue Risk Management System posted at 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 during a week (or shift changes). While these strategies are effective for population averages/overall, they do not address the weakest link in the workforce: those most likely to fatigue and/or get injured. Much work is needed in this area.

Conclusion

Based on a review of the literature, the authors offer the following advice to OSH professionals in transportation and manufacturing.

Transportation

A significant body of research highlights the effects of inadequate sleep (e.g., from sleep apnea, shift scheduling), night driving, weather (e.g.,

cloudy, 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 risk, an employer can modify routing/scheduling to alleviate some of these precursors. In addition, wearable sensors and on-vehicle systems (e.g., lane-departure systems, hard-brake-detection sensors) can provide real-time indicators of fatigue development during driving. An employer can view the data through simple dashboards that indicate which drivers are at risk. The employer 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.

Manufacturing

Fatigue is a demonstrated 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 discussions with several safety managers at large automotive companies, the authors learned that it is often easier to sell safety projects to upper management when these projects are combined with quality improvement initiatives. Management can see a return on investment on these projects when compared to a softer objective (e.g., reducing/eliminating the probability of a safety problem that has not occurred before).

In addition, OSH practitioners are encouraged to categorize their at-risk populations (e.g., unexperienced workers, obese and older workers). Existing ergonomics and safety models that consider an average worker cannot model these workers. Thus, a dashboard that monitors absenteeism, work performance and safety incidents can be used to trigger appropriate interventions.

A final word of caution: Fatigue detection systems do not mitigate or eliminate fatigue. OSH professionals should, therefore, embrace technology as a component of a safety system, not as a solution on its own.

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The researchers are currently midway through a 3-year study that seeks to determine how to quantify fatigue in individuals and help safety professionals enact policies that will reduce fatigue-related incidents. View a video on the study at <https://youtu.be/Pt4wojwLK8>.

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