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Fatigue monitoring in offshore energy operations: Research to Practice gaps

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Abstract

The oil and gas extraction (OGE) industry continues to experience an elevated fatality rate; from 2010-2014 fatality the rate in this industry was nearly seven times higher than that for all U.S. workers. OGE workers are exposed to intensive shift patterns and long work durations inherent in the OGE environment, which can lead to fatigue, thereby increasing risks of accidents and injuries. Fatigue, often defined as a physiological state of reduced mental or physical performance capability resulting from sleep loss, circadian phase, and workload, has been implicated as a critical risk in both offshore and onshore OGE operations. The aims of this study were to explore the effect of offshore shiftwork on physiological and subjective fatigue outcomes. 10 male workers (age: 31.3 (6.1) years; stature: 1.72 (0.1) m; weight: 85.24 (9.8) kg) were monitored throughout their daily shifts for six days using intrinsically safer physiological sensors (EQ02 LifeMonitor, Equivital^{TM}, Cambridge, UK) that recorded various physiological parameters at 250Hz and subjective fatigue scales were employed to obtain perceptions of fatigue. Results indicate that overall average ambulatory heart rate (an indicator of fatigue) were elevated for all participants and was highest and raised the most for those who started and ended their hitch on the day shift. The same measure was lowest and did not change for those who started on the day shift and swung to the night shift. The ambulation rates (a measure of movement) were higher later in the participants' hitch and this effect was seen primarily for those who started their hitch in the day shift. Participants' reports of fatigue were relatively high for acute fatigue and intershift recovery as well as for lack of effort and sleepiness; however, the physiological measures were not consistently or predictably correlated with the self-report measures of fatigue or activity. The study outcomes identified a critical gap in fatigue assessment in OGE operations; existing fatigue surveys for the general (or other) working populations are not comprehensive of OGE operations and are thus not applicable for OGE workers, nor are they validated against physiological fatigue outcomes in OGE workers.

Introduction

Worker fatigue is a critical occupational risk that has cost lives, injured workers, disrupted productivity, with economic losses estimated at $18 billion a year [1, 2]. This is a big problem, particularly in the oil and gas extraction (OGE) industry, as OGE workers are exposed to intensive shift patterns and long work durations, coupled with intense physical and mental workload inherent of the OGE environment. From 2003–2014, 1,331 OGE workers died while working, resulting in an annual fatality rate seven times higher than that for all U.S. workers [3]. Fatigue, generally defined as a physiological state of reduced mental or physical performance capability resulting from sleep loss, circadian phase, and workload, has been implicated as a serious risk factor in a majority of the cases affecting worker safety [4, 5]. Both industry and federal agencies have determined that "*decreasing fatigue-related injuries and fatalities in the OGE industry*" is one of their top strategic research (to practice) priorities.

In offshore operations, fatigue is predominantly considered a consequence of two sources: 1) an insufficiency of sleep (or poor quality of sleep), and 2) the 24-hour circadian cycle in wakefulness and alertness. Fatigue, due to sleep loss and extended wakefulness, is typically managed through shift and time management. Work schedules are typically 12 hours of work followed by 12 hours off-work, in two shifts, day and night. Structurally, this provides the opportunity for rest; however, making time for rest and getting rest are not necessarily the same. Night shift workers report not getting enough sleep during the day, as much as two to four hours less than they would if working a day shift. Maintenance of peak performance is time-limited and is compromised at night. There is considerable evidence that incidents/accidents will be more likely to occur between 3 am and 6 am in the morning – corresponding with the low point in the circadian cycle. Additional sleep loss is reported when workers transition between shifts. Because ~40% fatalities in OG workers occur due to transportation crashes, particularly as workers return home from their offshore shifts, a recently adopted remediating fatigue management practice observed in offshore environments are "swing shifts". In the swing shifts, workers' shifts (either day or night) are rotated mid-way through their stay offshore [19, 20] to ensure that workers are adapted to day shifts their last day offshore. However, a disadvantage of swing shift is that the workers need to adapt to a new rhythm while on their offshore assignment; these changes in rhythms introduce concerns for the health and safety of the workers [19, 21]. Despite the 12-hours of non-work, sleep debt due to shift work and in particular swing shifts can adversely affect operator physiological responses and cognitive performance. Short-term sleep loss is associated with diminished clinical performance, cognitive functioning, memory, and vigilance. For example, the Accreditation Council on Graduate Medical Education standards limit resident work to 80 hours per week. Sleep deprivation ranging from 24 – 48 hours has shown to impair performance across many cognitive domains. This is alarming, as drill workers on a typical 14-day rotation will work 84 hours in a week. Another source of fatigue in offshore environments, particularly for drill operators, may originate from the task itself.

One of the major barriers that currently impact the development of effective fatigue mitigation practices in OGE workers is the assessment of fatigue. Fatigue is a complex multidimensional construct, and its definition and assessment differs based on different occupations [6, 7]. Objective indicators of fatigue may include operational outcomes, such as operator performance, or physiological outcomes, such as elevated heart rate and respiration rates. Subjective indicators of fatigue may be obtained using surveys, interviews, sleep logs, etc. The selection of a valid indicator to assess fatigue in the complex, multi-component tasks of an offshore environment is challenging. Fatigue may be distinguished not just in relation to the sources, i.e., sleep loss due to shiftwork or intense workload, that aggravate the condition but also to the responses that indicate a fatigued state, i.e., performance decrement or elevated heart rate. For example, decrements in performance metrics may indicate a fatigued state but these performance changes alone cannot indicate the source of the fatigue and thus cannot inform fatigue mitigation strategies. To assess operator fatigue in offshore OGE environments, it is important to first distinguish the physiological consequences (or cost to maintain performance) of operator workload [22].

The primary aim of this study was to determine the relationship between shiftwork and physiological responses in operators in offshore OGE operations. A secondary aim was to explore the effectiveness of subjective scales available in the literature to assess operator fatigue levels. Operators employed in offshore oil and gas operations were followed during one of their offshore work assignments for six days, and quantitative data (inventory of various fatigue scales and physiological monitoring) was collected.

Methods

Participants.

Participants were recruited onboard a drillship in the Gulf of Mexico using a protocol approved by Texas A&M's Internal Review Board through the ship medic. Participants' recruitment was based on their ability to take time away from their post to speak to the researchers and, after being informed of the requirements and purposes of the study, their willingness to participant. Upon consent, they completed the first set of surveys; a demographics data (including age, height, weight); and work history data (years in the industry and years in current job) (see Table 1). They then participated in a structured interviewed regarding their perceptions of fatigued (results not presented here) and were fitted with the sensors. The entire protocol was about 1 ½ hours. Shift times on the rig was categorized into Day (6 am – 6 pm and 12 pm – 12 am) and Night (6 pm – 6 am and 12 am – 12 pm) shifts. Original shift times for each operator was recorded (refer to Table 2) and 6 of the 10 operators underwent swing shifts.

Table 1. Descriptive Statistics of operators. N = 10

	Mean	SEM	Median	Min	Max
Age (yrs.)	31	2.06	29.5	23	41
Height	67.7	0.87	67.5	63	72
Weight (lbs.)	192.1	6.75	190	170	250
Years in Industry (yrs.)	8.2	1.95	5.5	2	20

Years in Current Job (yrs.)	3.2	0.55	3	1	7

Table 2. Number of operators in each shift. N = 10

Shift Time	Earlier in Hitch	Later in Hitch
6am	2	3
12pm (noon)	5	0
6pm	1	1
12am (midnight)	2	6

Procedures.

After study familiarization, various fatigue surveys and a work questionnaire was administered to each operator. Starting with the first day of participation, operators were instrumented with the physiological sensor, which consisted of a sensor belt worn across their chest and the sensor was attached to the belt. The sensors were instrumented at the start of each operator's shift and returned back to the research team at the end of each shift.

Measurements.

Main study outcomes collected during the data collection phase included the inventory of fatigue scales, as well as the work questionnaire, collected on day 1, and physiological responses collected continuously for 6 days. Some of the participants completed the inventory of fatigue scales additional times throughout their hitch, i.e. 10 completed the first surveys, 5 participants completed a second set of survey, and 2 completed a third set of surveys—creating a total of 17 complete set of surveys. Given that not all of the participants complete the surveys three times, these surveys were all treated as individual responses for statistical analyses.

Inventory of fatigue scales. The operators completed several paper-based questionnaires available in the fatigue literature that provided subjective assessments of different aspects of fatigue that are commonly experienced by OGE operators. The Swedish Occupation Fatigue Inventory (SOFI) provided 5 fatigue sub-scale assessments (physical exertion, physical discomfort, sleepiness, lack of energy, and lack of motivation) [14], the Occupational fatigue Exhaustion Recovery (OFER) provided 3 sub-scales (acute fatigue, chronic fatigue, and inter shift recovery) [15], the Fatigue-Related Symptoms Questionnaire (F-RSQ) provided 2 sub-scales (physical and mental fatigue) [16], and the Fatigue Scale (FAS) provided one unidimensional score of overall fatigue [17]. Additionally, a questionnaire on working environment, which included items specific to the physical, mental, and psychosocial demands, was administered to identify work risk factors.

Physiological indicators of fatigue. Operators were instrumented with ambulatory sensors (EQ02 LifeMonitor, Equivital^{TM}, Cambridge, UK), capable of logging physiological data describing physiological status, such as electrocardiography, respiratory inductance plethysmography, posture/activity, multipoint skin temperature, and core temperature collected at 250 Hz. The validity, reliability, and applicability of this system for sleep [23] and ambulatory monitoring of multiple physiological parameters during construction and firefighting work have been previously demonstrated [24-26]. Based on the extant physiology literature, heart rate (HR) was selected as the primary fatigue indicator as it has shown to be sensitive to changes in physical and mental fatigue [11-13], as well as sleep and circadian issues [27-31].

Beats per minute was obtained from the raw electrocardiogram (ECG) signals based on [36]. Excluding artifact readings and outliers from ambulatory ECG was followed based on [32, 33] in conjunction with accelerometer data obtained from the sensor [34, 35]. All physiological data during the operator's 12-hour shift was primarily categorized based on activity (stationary and ambulatory). For each activity classification, stable HR bouts (± 5 bpm) of at least 4 minutes duration were identified over the course of a work day. From the identified stable HR bouts the following parameters were computed per activity: the minimum, average, and maximum HR levels, as well as average ambulation during the ambulatory activities for each of the 6 days. These parameters provided greater resolution and sensitivity of overall HR patterns observed across each activity classification during the course of a shift.

There were three main sets of physiological measurements necessary for statistical analysis. The first sets were those from the day the participants completed the surveys. To capture these data, the measures described above for the day the participant completed the survey were used. The next two were measurements from immediately before and after the participants completed a swing shift (for those who changed shifts). To capture these measurements—for those participants who had a swing shift—we took the average of the measures three days before the swing shift (earlier in the shift) and three days after the measure (later in the shift). For those who did not change shifts during their hitch, we identified the middle day of the data collection period and took the average of the measures three days before and three days after that middle day. By using this manner, it was possible to compare the physiological measures of those who did and did not change shift in a somewhat equitable way, albeit imperfect.

Statistical analyses.

To identify effects of time on hitch (Within: earlier/later in the hitch), Shift Time (Between: Day/Night), and Swing (Between: whether or not the person changed their shift day from day to night or vice versa), effects the physiological variables, separate Mixed design Repeated Measure ANOVA was done for each of the heart rate variables (min, max, & avg HR) for stationary and ambulatory activities, as well as average ambulation during the ambulatory activities. To identify relations between the fatigue scales and the physiological variables, Pearson's correlations were done with the survey responses and the physiological measures from the day the person completed the survey.

Results and Discussion

Physiological profiles of operator fatigue with shiftwork.

Descriptives of the physiological fatigue indicators are presented in Table 3. In general, physiological responses were higher during ambulatory activities when compared to stationary activities. These findings provide support to the formulation of stable HR profiles derived for field research, however, further validation of these profiles are warranted in controlled (simulated) work environments.

Table 3. Heart rate (HR) measures for the entire period participants wore the monitors

	Mean	SEM	Median	Minimum	Maximum
Activity classification: Stationary					

Minimum HR (bpm)	69.4	3.4	68.6	53.2	87.8
Average HR (bpm)	87.4	5.2	84	69.7	123
Maximum HR (bpm)	121.9	11.4	103.3	89.4	187.6
Activity classification: Ambulatory					
Minimum HR (bpm)	71.9	3.4	71.3	56.2	92.2
Average HR (bpm)	108.9	7.8	107	81.4	152.7
Maximum HR (bpm)	180.7	15.4	180.3	106.9	263.2
Average Ambulation					
(scale 1 - 3)	1.4	0	1.3	1.2	1.6

There were effects for max. ambulatory HR and Ambulation, while all other physiological indicators were not affected by the study variables (*p's* > 0.10). The max. ambulatory HR generally increased over the hitch, however this effect did not reach traditional levels of significance (F(1, 6) = 3.55, p = 0.109, $\eta_p^2 = 0.371$). There was a significant difference between the max. ambulatory HR for the Day and Night early in hitch shifts (F(1, 6) = 15.9, p = 0.007, $\eta_p^2 = 0.73$) with the Day shift having higher HR levels (MEAN = 198.5 bpm, SD = 11.2) than the Night shift (MEAN = 141.9 bpm, SD = 15.4). There was an interaction between shift earlier in hitch and swing (Non-swing/Swing) with the difference in max. ambulatory HR between Non-swing/Swing being much higher for the Day shift earlier than for the Night shift earlier, F(1, 6) = 7.9, p = 0.03, $\eta_p^2 = 0.57$.

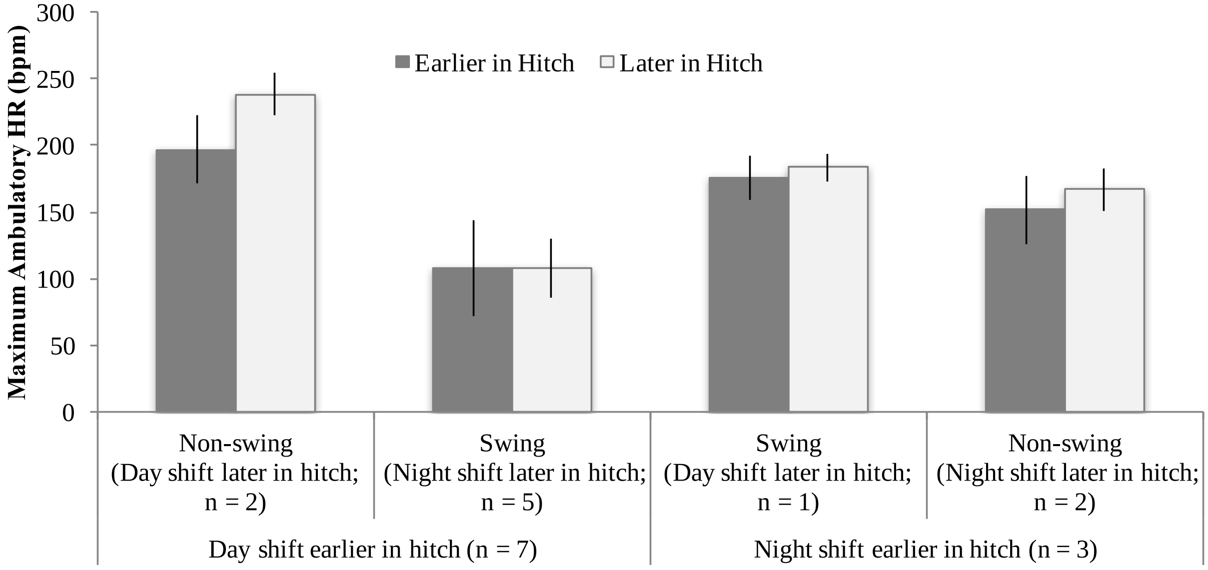

Figure 1. Max. ambulatory HR by Time of first shift (Day/Night earlier in hitch), Time of second shift (Day/Night later in hitch), and change during the hitch (Earlier/Later). Error bars represent the standard error of the mean. N = 10

The avg. ambulation increased over the hitch (F (1, 6) =5.97 p = 0.05, η_p^2 =0.50) and there was an interaction between change in ambulation over the shift and Day/Night earlier in the hitch with there being a greater increase in ambulation over the shift for those who started their shift during the day than those who started at night, F (1, 6) =6.27 p = 0.05, η_p^2 =0.51. All other possible main effects or interactions had p's > 0.06.

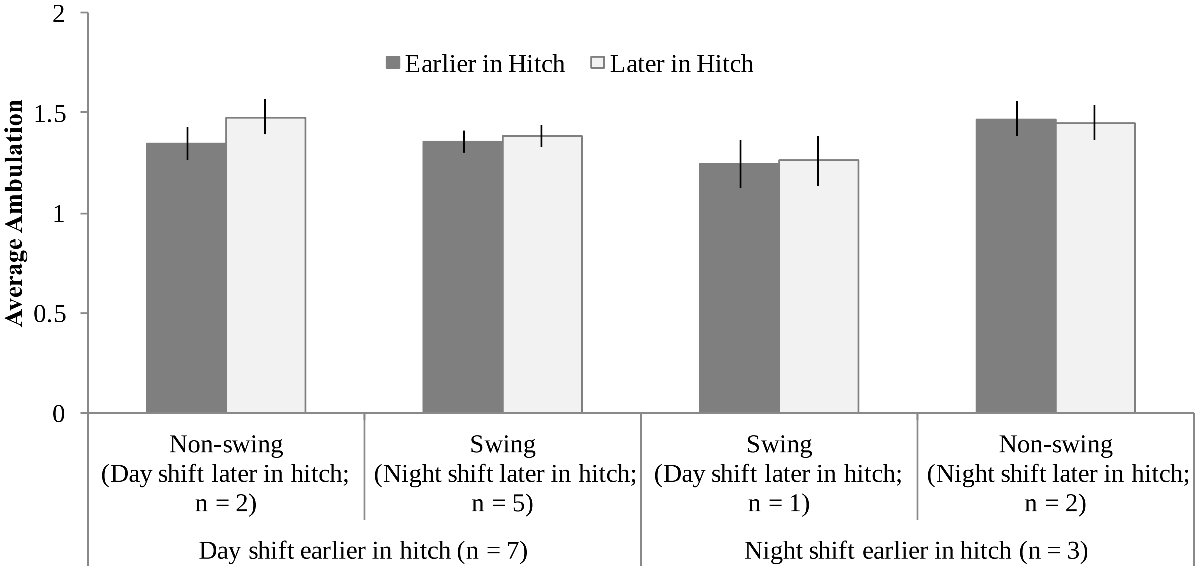

Figure 2. Average Ambulation by Time of first shift (Day/Night earlier in hitch), Time of second shift (Day/Night later in hitch), and change during the hitch (Earlier/Later). Error bars represent the standard error.

In general, studies have shown association between swing shifts and altered physiological changes, and that these alterations further depend on time of shift [19, 21]. In the present study, the earlier/later in the hitch differences (or lack thereof) in physiological indicators of fatigue in operators who underwent swing shifts were lower than those who did not. Against expectations, the operators who started in the day shift and remained in the day shifts showed the most increase in HR levels. It is likely that their job demanded greater efforts, which is moderately evident from the ambulation data (see Figure 2). It is also possible that environmental factors, such as temperature, may have influenced HR responses. Due to the small sample size in each of the sub-groups identified, results need to be cautiously interpreted. Finally, even though the HR levels of operators on swing shifts, particularly those that began on a night shift and ended on a day shift, remained relatively similar, on an average, most of these operators had HR levels well above the average resting HR range of 60-100 bpm.

Operator perceptions of fatigue.

Descriptives of the fatigue scales are presented in Table 4. In general, operators perceived higher acute and inter shift fatigue (from the OFER scale), lack of effort and sleepiness (from the SOFI scale), and increased Work Demand, Work pace, and Repetitive Strain Injury (from the working environment survey).

Table 4. Descriptives of surveys and subscales. The response scales are indicated with each survey. Higher values are indicative of higher levels of fatigue.

	Mean	SEM
FAS (1 – 5)	1.76	0.13
F-RSQ (0 – 8)		
Overall	2.12	0.46
Cognitive	1.47	0.41
Physical	0.65	0.21
OFER (0 – 6)		
Acute Fatigue	4.14	0.41
Inter shift Recovery	3.94	0.34
Chronic Fatigue	2.02	0.28
SOFI (0 – 6)		
Lack of Effort	3.45	0.49
Sleepiness	3.31	0.46
Physical Effort	1.82	0.41
Lack of Motivation	1.64	0.38
Physical Demand	1.51	0.29
Working Environment (1– 6)		
Work Demand	5.28	0.14
Work Pace	4.78	0.19
Repetitive Strain Injury	4.7	0.21
Physical Environment	2.83	0.25
Comfort	2.23	0.11
Pain	2.09	0.23
Safety	1.98	0.15

Comparison of physiological and survey responses.

Pearson Correlations of physiological responses from the day the participants completed the surveys and their survey responses is presented in Table 4. The primary purpose of correlation analyses was to identify whether indicators of fatigue, across objective and subjective methods, measured operator fatigue similarly. Physical discomfort was positively associated with minimum HR during stationary activities; however significant correlations between FAS scale and maximum HR during ambulatory activities and inter shift recovery sub-scale from OFER and minimum HR were found, but opposite to what was expected. Additionally, when comparing perceptions of work risk factors and physiological responses, Work Demands was the only risk factor strongly correlated to maximum HR during stationary activities. While repetitive strain risk was correlated across several HR variables, the observed association was against general expectations.

Table 4. Pearson Correlations of physiological responses from the day the participants completed the surveys and their survey responses. Significant correlations are highlighted in bold and italics and have an *. The measures on Physical Discomfort and Repetitive Strain Injury were the only ones to correlate with more than one physiological measure (2 and 3 respectively).

	Stationary Activities			Ambulatory Activities			Ambulation
	Min HR	Avg HR	Max HR	Min HR	Avg HR	Max HR	
Measures of Fatigue							
FAS (Usual fatigue)	0.14	-0.16	-0.19	-0.22	-0.22	***-0.54****	0.30
F-RSQ (Overall)	-0.02	-0.47	-0.13	-0.29	-0.17	-0.12	0.34
F-RSQ (Physical)	-0.01	-0.38	-0.34	-0.33	-0.33	-0.43	0.14
F-RSQ (Cognitive)	-0.02	-0.32	0.04	-0.15	-0.02	0.09	0.30
SOFI (Lack of Effort)	0.04	-0.34	-0.17	-0.33	-0.19	-0.11	0.23
SOFI (Lack of Motivation)	0.36	0.01	0.18	0.04	0.23	0.07	***0.55****
SOFI (Physical Discomfort)	***0.59****	0.12	0.14	0.13	0.25	0.10	***0.60****
SOFI (Physical Effort)	0.47	0.10	0.19	0.11	0.26	0.13	***0.61****
SOFI (Sleepiness)	-0.03	-0.41	-0.05	-0.34	-0.15	-0.14	0.32
OFER (Chronic Fatigue)	0.33	-0.04	0.08	-0.11	0.12	-0.14	0.38
OFER (Acute Fatigue)	-0.02	-0.31	-0.06	-0.32	-0.18	-0.30	0.13
OFER (Inter shift Recovery)	-0.24	-0.47	-0.10	***-0.60****	-0.27	-0.44	0.14
Working Environment							
Physical Environment	0.01	-0.29	-0.47	-0.20	-0.26	0.01	0.23
Repetitive Strain Risks	0.35	***0.54****	0.40	0.32	***0.56****	***0.63*****	-0.13
Pain	0.11	-0.18	0.11	0.12	0.02	0.29	-0.36
Work Pace	0.00	-0.48	-0.45	-0.35	-0.35	-0.04	-0.04
Work Demands	-0.01	-0.24	***-0.55****	-0.23	-0.45	-0.20	0.44
Safety	-0.37	-0.10	0.11	-0.12	-0.07	-0.38	-0.11
Comfort	-0.20	-0.22	0.01	-0.39	-0.07	0.16	0.30

*** Correlation is significant at the 0.01 level (2-tailed).*

** Correlation is significant at the 0.05 level (2-tailed).*

It is clear from this analysis that except for the physical discomfort sub-scale from SOFI, none of the subjective fatigue scales, or the work risk factor survey, are significantly associated with any of the HR variables. This could be due to: the low sample size; that these scales are not associated with the attributes of fatigue associated with HR; or that the existing measures are not effective at capturing fatigue in the OGE environment. While the physiological profiles highlighted the detrimental effects of shiftwork (particularly swing shift practices) on HR responses, the lack of association between operator perceptions of fatigue using existing scales and the physiological responses is concerning. These findings, while preliminary, highlights an important gap that an OGE domain-specific fatigue assessment method is needed that is validated against physiological outcomes of fatigue, particularly given that there exist effective fatigue scales for other industry domains [14, 18].

In regards to the feasibility of adopting survey-based fatigue assessments for offshore operations, we observed that on average, it took operators approximately 45 minutes to complete all of the questionnaires and a majority of the questions and wording were not clear to them. Future qualitative studies are warranted that determine the temporal requirements of survey measurements, i.e., when and how often should surveys be administered. Moreover, more information is needed on how the surveys need to be administered. Based on the researchers' experience and informal feedback from operators, it was suggested that fatigue assessment methods tailored to align with existing worker behavior on safety reporting methods have better compliance rates and chances of sustainability than introducing new reporting behaviors. These initial findings clearly indicate that using fatigue questionnaires from the literature is not feasible, comprehensive, or sufficiently relevant for the OGE workers. This presents challenges in identifying high-risk workers and developing fatigue management practices that are targeted and effective in reducing fatigue-related incidents in the OGE industry.

Implications for Fatigue Research 2 Practice

Physiological (and wearable) fatigue monitoring systems are gaining rapid attention, particularly in the transportation and aviation sectors [8-10], however given the hazardous nature of OGE work conditions, passive or real-time monitoring of physiological indicators of fatigue present safety risks due to sensor materials being explosion-prone in hazardous volatile rig environments. As such, subjective fatigue assessment methods may in fact enable viable, safe, and sustainable evaluations of fatigue risks in OGE work environments. The development of a reliable, sensitive, and valid fatigue assessment survey that takes into consideration not only the various OGE-specific sources of fatigue, but also the barriers associated with effective fatigue assessment in OGE operations (identified in this study) are imperative. Without access to such methods, developing effective evidence-based controls or preventive strategies for reducing fatigue-related injuries and fatalities in the OGE industry will likely remain limited.

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