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The Impact of Fatigue on Hazard Recognition: An Objective Pilot Study

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Abstract: The construction industry is demanding, dynamic, and complex making it difficult for workers to recognize hazards. The nature of construction tasks exposes workers to several critical risk factors, such as a high rate of exertion and fatigue. Recent studies suggest that fatigue may impact hazard recognition in the construction industry. However, most studies rely on subjective measures when assessing the relationship between physical fatigue and hazard recognition, limiting such studies' efficacy. Thus, this study examined the relationship between physical fatigue and hazard recognition using a controlled experiment. Worker fatigue levels were captured using physiological data and a subjective exertion scale. The findings confirmed that physical exertion plays a significant role in hazard recognition skills ($p < 0.05$). This research contributes to theory and practice by providing a process for objectively assessing the influence of physical fatigue on worker safety and providing construction professionals with some critical insight needed to improve workplace safety.

Key words: fatigue, hazard recognition, exertion, heartrate variability, safety performance

1. INTRODUCTION

In 2020, 4,764 deaths occurred in occupational settings, with the construction industry accounting for 21% of all fatalities – the highest rate among all sectors [1]. This is primarily due to construction operations' dynamic and hazardous nature, which makes it difficult for workers to identify risks that could cause accidents [2]. Moreover, relative to other industries, the construction industry reports a significantly higher rate of injuries caused by physical exertion [1]. Practitioners have applied several techniques to prevent workplace accidents [3], [4]; however, workplace accidents continue to occur at statistically the same rates as in the previous decade [1]. Personal factors that influence workers' situational awareness have been researched, and physical exertion and fatigue have emerged as critical components [5].

A high level of physical exertion typically leads to worker fatigue. Fatigue indicates a worker's lack of efficiency and reluctance to expend effort [6]. Fatigued workers are 1.62 times more likely to be engaged in an occupational accident [7]. Taherpour et al. [8] found a strong correlation between occupational fatigue and Hazard Recognition Performance (HRP) in the construction industry. Similarly, Namian et al. [9] posited that lack of recuperation between work shifts and acute fatigue have a detrimental influence on worker safety performance. Few studies have used biosensors to track construction workers' fatigue [10], [11]; nonetheless, much research has relied solely on subjective exertion or fatigue assessments, which are prone to cognitive biases [10]. Consequently, it is necessary to objectively monitor physical exertion and fatigue and analyze their influence on workers' HRP.

Therefore, this pilot study aims to investigate the influence of exertion on HRP using data from students in a pilot study. The participants' heart rate (HR) and heart rate variability (HRV) were captured as objective measures for physical fatigue, and the Rating of Perceived Exertion (RPE) scale was used to supplement the physiological data gathered using biosensors. The findings of this study are useful for construction professionals who aim to improve worker safety performance through enhanced fatigue management techniques. In addition, the present study provides future directions to construction safety researchers interested in situational awareness research and worker fatigue.

2. BACKGROUND OF THE STUDY

2.1. Hazard Recognition

Hazard recognition is essential for an effective workplace safety management system and for personnel to maintain excellent safety behavior [3]. The fundamental purpose of safety management programs is to avoid workplace accidents, but the effectiveness of construction safety management processes on the jobsite largely depends on workers' hazard recognition skills [2]. In other words, if workers' safety risk awareness is poor, safety management practices will be ineffective. Major workplace accidents will likely occur when worksite safety hazards are not identified [2]. Therefore, it is important to understand the role of critical risk factors, such as fatigue, on hazard recognition. Fatigue is unique to each worker and contributes to high incident rates [5], [9].

2.2. Fatigue

Fatigue is a vital issue prevalent in today's construction work environment [6]. The type of task, work environment, and work intensity all impact a worker's fatigue level [12]. The two types of fatigue workers experience are physical and mental fatigue [6]. Physical fatigue is a concentrated sensation caused by overworked muscles, but mental fatigue is experienced throughout the body accompanied by sentiments of indolence and aversion to any form of labor [6]. Fatigued workers are less productive because they tend to have reduced performance, slow reaction time [13], and a high tendency for risk-taking [2].

Few studies have examined the impact of physical fatigue on workers' hazard recognition in the construction industry. Namian et al. [9] examined worker fatigue and safety performance and reported that acute fatigue significantly influences hazard identification and safety perception. Taherpour et al. [8] further stated that fatigue levels and HRP have a negative association. Similar to the findings of Namian et al. [9] and Taherpour et al. [8], Techera et al. [14] suggested that fatigue lowers workers' HRP. However, none of these studies assessed the impact of fatigue on workers' hazard recognition performance using objective measures.

2.3. Wearable Physiological Sensors for Fatigue Measurement

To effectively manage worker exertion, it is vital to be able to detect and measure it. Currently, no one technique or variable can effectively evaluate exertion as it manifests in various ways and could differ from person to person [12]. However, a good fatigue index should be able to distinguish between situations when participants are fatigued and when they are not.

Due to the limitations of subjective scales, studies have employed objective methods to quantify fatigue by using physiological data such as brain activity, HR, and HRV [15] obtained from biosensors. The number of times a human's heartbeats per minute (bpm) is called HR. When workers are exerted, their HR can rise to over 120 bpm [16]. Equation 1 provides a formula for estimating a human's maximal

HR based on their age [17]. When an individual's HR falls between 64 – 76% of their maximum HR, they have been subjected to moderate-intensity physical activity, and physical activities are considered vigorous-intensity when the HR falls within 77 – 93% [17].

$$20 - Age\ (in\ years) = Maximum\ heart\ rate\ (in\ bpm) \tag{1}$$

HRV is another metric for the cardiovascular system, and it is a promising tool for detecting fatigue [18]. HRV measures the change in time from one heartbeat to the next [19]. When individuals are exerted, disturbances are induced in their autonomic nervous system (ANS), and their HRV decreases [15]. Higher HRV increases energy, physical, and cognitive performance [18].

3. RESEARCH METHODOLOGY

Fatigue is constantly present in construction due to the dynamic workplace and arduous construction tasks [9]. Based on existing literature, the central hypothesis for this study is that physical exertion has a negative influence on hazard recognition. The steps taken to test this hypothesis are explained in the following sections.

3.1. Experimental Study

Eight male students from the University of Alabama were recruited to participate in the present study as a pilot test. This study was approved by the Institutional Review Board (IRB) at the University of Alabama. The construction students' age ranged between 20 and 28, and the mean (±), Standard Deviation (SD) of their heights, weights, and standardized maximal voluntary contraction (MVC) force are 181.25 ± 8.8 cm, 188.4 ± 48.6 lbs., and 35 ± 10.2 lbs., respectively.

The experimental investigation entails completing a dumbbell-based exercise designed to fatigue a participant. The experimental methodology was adapted from Hwang et al. [20]. The investigation was split into two sessions and was completed at room temperature (74^{o}F) in an ergonomics-friendly laboratory. Consent was obtained from participants in the first session, followed by an introduction to the research experimental protocol and devices. Participants were equipped with a wireless biosensor (Zephyr Bioharness) worn on their chest region, as shown in Figure 1, which monitors HRV and HR. The baseline data for each participant were obtained during a 20-minute rest period. Next, the research team assessed each participant's MVC using a standardized 1 repetition maximum (1RM) protocol with dumbbell bicep curls on the dominant arm, as per the American College of Sports Medicine (ACSM) guidelines [21].

The second session for each participant took place at least 96 hours after the first to allow for any muscle soreness that may have occurred because of the first session to dissipate [22]. The participants completed a 24-hour history form, which the researchers reviewed to ensure that they followed the pre-test instructions. The instructions included staying hydrated and abstaining from food, tobacco, alcohol, caffeine, and supplements for at least 3 hours before the assessment. In addition, participants were asked to avoid exercise or strenuous physical activity on the day of the assessment and get an adequate amount of sleep (minimum 6 hours) the night before the evaluation.

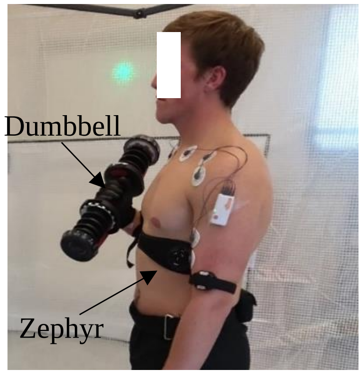

Figure 1. A participant conducting the experiment

The participant was equipped with Zephyr to monitor HR and HRV. Using a sample case image extracted from a study by Namian et al. [23], the researchers described construction safety hazards and classification to the participants while they were resting. Next, the image was removed, and the participants were given a new case image to identify all the hazards they could locate in the picture. Following the 20-minute rest period, participants were asked to begin the curling exercise. Using a dumbbell and a timed metronome, each participant was instructed to stand erect while moving their dominant forearm through a complete range of motion at a rate of 15 repetitions per minute. Each participant was asked to perform dumbbell curls until they could not continue. The RPE was used to assess subjective exertion, and participant HR and HRV were recorded. As soon as participants finished the exercise, they were asked to review another case image and identify potential hazards. The mean trial time for all the participants was 10 ± 3.8 minutes.

3.2. Fatigue Detection

As discussed in the Background section, the present study utilizes HRV and HR as objective measures of worker fatigue. In addition, the present study assessed subjective fatigue using the 1-10 RPE scale. RPE was chosen because it is a well-accepted method for evaluating participants' exercise intensity and is already utilized in construction research [24]. Although RPE is a good predictor of how hard individuals exert their muscles, cognitive bias might affect it [25].

3.3. Hazard Recognition Measurement

The research team presented two case images representing conventional construction activities embedded with work-related hazards to all the participants – one before and another after the exercise. Equation 2 was used to calculate each participant's HRP for each case image.

$$HRI_{iw} = \frac{HI_{iw}}{TH_i} \tag{2}$$

Where HRI_{iw} = hazard recognition index for case image *i* for worker *w*; HI = the number of hazards identified by the worker *w* for image *i*; and TH = the total number of unique hazards present in image *i*.

These case images have been reviewed and validated by construction safety practitioners and industry experts [23]. The first and second images have 11 and 14 unique hazards, respectively, according to the experts' reported lists of hazards. Upon completing the interviews with participants, results from the data analysis indicated that they did not identify any new hazard for each case image.

4. DATA ANALYSIS AND RESULTS

For this study, several biological measures were gathered, including RPE, HR, HRV, and HRI. Several approaches were explored to determine whether the individuals were fatigued. First, the research team evaluated the HR percent over time chart in the Zephyr OmniSense Analysis software, which revealed that the participants were engaged in moderate-intensity physical activity. Second, the intensity of physical activity among the participants was manually estimated using the guidelines from Riebe [17]. Participants post-exercise HR was over 61% of their maximum HR, on average, which is considered moderate-to-high HR (average HR was just shy of 120 bpm). In addition, the experiment lowered the average HRV, which indicates participants were stressed and fatigued after the experiment [15]. Subsequently, the research team assessed the RPE score reported by participants. The average RPE score recorded by the participants at the end of the experiment was eight (8), indicating "*I can grunt in answer to your questions and can only hold this pace for a short time period*," which also confirmed the participants were fatigued.

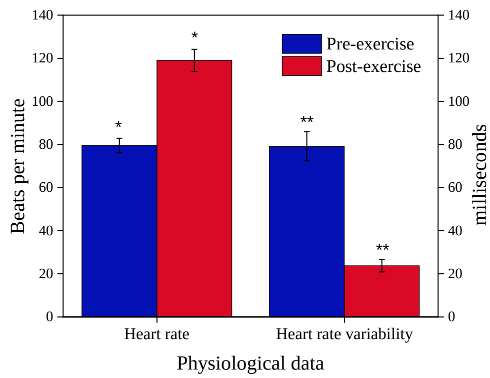

Figure 2. HR and HRV for pre-and post-exercise for participants
Note: The bars with * and ** respectively have significant differences between them

Normality tests were performed on the pre-and post-exercise HR and HRV data, and the Shapiro-Wilk test revealed that both variables fulfilled the assumption of normality ($p > 0.05$). As a result, a paired samples t-test was used to investigate the effect of exertion on participant HR and HRV, with the results provided in Figure 2. The HR of the participants for post-exercise was found to be significantly higher than that of the pre-exercise [$t(7) = -7.663$, $p < 0.001$]. As for HRV, the test showed that the post-exercise HRV was significantly lower than the pre-exercise HRV [$t(7) = 6.565$, $p < 0.001$]. This suggests that the exercise significantly impacted the participants' HR and HRV. Moreover, the mean of the pre-exercise HR = 79.50 bpm, and HRV = 79.13 ms were similar, indicating that the participants were at rest before the exercise [26]. On the other hand, the mean ± SD of the post-exercise HR was 119 ± 14.51 bpm, which indicates that the participants were fatigued [16].

After establishing that the participants were fatigued, a statistical test was conducted to assess the impact of fatigue on HRI. The pre-and post-exercise HRI variables were tested for normality, and the Shapiro-Wilk test showed that one of the variables violated the assumption of normality ($p < 0.05$). Hence Wilcoxon signed-rank test was performed. The test outcome showed that fatigue had a statistically significant impact on the hazard recognition performance of the participants, $z = -2.527$, $p = 0.012$, with a large effect size ($r = 0.632$). As shown in Figure 3, participants' HRI reduced by 13.6% after fatigue set in.

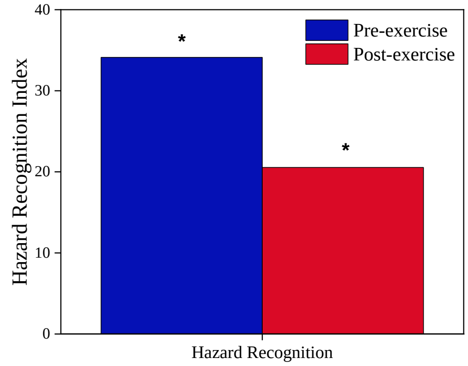

Figure 3. Hazard Recognition Index for pre-and post-exercise for participants

A Pearson correlation coefficient was computed to assess the linear relationship between the RPE and the physiological data of the respective participants. There was a statistically significant, positive correlation between RPE and HR, Pearson coefficient varied from r(4) = 0.983, $p = 0.017$ to r(11) = 0.877, $p < .001$. Additionally, there was a negative correlation between the RPE score and the HRV, Pearson coefficient varied from r(4) = -0.981, $p = 0.019$ to r(11) = -.934, $p < .001$.

4.1. Discussion of findings

When workers are subjected to a physical task, they physically and mentally struggle to remain alert after fatigue sets in [13]. The Wilcoxon signed-rank test revealed that the exercise caused the participants to be fatigued significantly ($p < 0.001$), raised their HR by 40 bpm, and lowered their HRV by 55 milliseconds at the end of the exercise. There was a positive association between the RPE and HR, and a negative association between the RPE and HRV. The biosensor accurately detects exertion throughout physical activity, and the data from such biosensors may be utilized to construct prediction algorithms that can forecast worker fatigue. Furthermore, the statistical test revealed that exercise significantly influenced the participants' hazard recognition performance. The participants' hazard recognition performance was significantly reduced after they became fatigued. This result supports the findings of Namian et al. [9] and Xing [24], that fatigued workers identify fewer hazards and are more prone to occupational accidents because they tend to behave in an unsafe manner in the workplace.

Furthermore, fatigue reduces construction workers' situational awareness, making them more vulnerable to workplace accidents [27]. Construction processes may become unnecessarily expensive because of fatigue's direct and indirect effects on the jobsite [2]. As a result, construction employers and safety managers must take preventive measures to alleviate workplace fatigue by designing less tiring duties and schedules, investing in and encouraging workers to attend fatigue training, and automating construction tasks [9], [24].

5. CONCLUSION

Improving construction workplace safety has been a critical priority for construction professionals and academics. This pilot study aimed to investigate the effect of exertion on participants' hazard recognition performance (HRP). A questionnaire with case images was used to measure the participants' HRP pre- and post-exercise. To establish the participants' fatigue state, the subjective exertion scale was used to complement the objective data from the biosensor, and there was a significantly high correlation between the subjective scale and the physiological data. The outcome of statistical tests established that the participants were moderately fatigued from the exercise, which lowered their hazard recognition performance by 13.59%. This research is one of the first to experimentally investigate fatigue's effect on hazard recognition ability in the construction industry using objective metrics. The findings of this study provide a foundation that will support future studies focused on assessing the role of fatigue on situational awareness. Moreover, the results suggest that practitioners could include wearable biosensors as a tool for fatigue management.

The limited sample size of this study is a limitation; thus, future studies should recruit a larger sample size of construction workers with different levels of work experience. Moreover, researchers should utilize a sample consisting of male and female construction workers subjected to construction-specific tasks. To eliminate the possibility of order bias and/or image cofounding effect while testing participants' HRP, future studies should use more than one case image in each trial and/or randomly swap the case images for different participants.

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