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Assessment of Physical Demand in Bridge Rehabilitation Work by Physiological Status Monitoring

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Transportation construction projects involve long working hours where workers are subjected to intensive tasks such as hard manual work and compulsive working postures. Physically demanding work can be fatiguing as well as alter the mental state, which may, in turn, lead to decreased productivity, poor judgement, and ultimately more accidents and injuries. Therefore, monitoring and controlling physical demand is of paramount importance to sustain productivity without undermining workers' safety and health. The objective of this study is to apply a non-intrusive system to monitor and assess the physical demand of transportation construction workers using the percentage of Heart Rate Reserve (%HRR) as a measure. For this study, five bridge maintenance workers volunteered to record their physiological metrics while performing various construction and maintenance tasks. The case study results showed that bridge maintenance workers had an average daily %HRR over %30 which according to the literature can be considered as having a "high" cardiovascular load during an eight hour working day. The primary contribution of this research is the assessment of the physical demands of transportation construction workers with respect to acceptable physiological thresholds and boundaries. The application of the present approach can support construction workers in preventing excessive cardiovascular overload.

Key Words: Physical demands, Occupational health and safety, Wearable devices, Heart rate reserve, Transportation Construction workers

Introduction

The construction industry consistently maintains high rates of injuries and fatalities compared to other industries. Working on construction sites involves risk, can be physically demanding, and is significantly impacted by environmental conditions. Many construction activities involve heavy lifting, unusual work postures, vibrations, pushing and pulling, and forceful exertions (Hartmann and Fleischer 2005). Specifically, transportation construction projects involve long working hours where workers are subjected to intensive tasks such as hard manual work, heavy weightlifting, and compulsive working postures (Roja et al. 2006). These activities can result in fatigue and exhaustion due to their high physical demand. Some of these activities can cause immediate injuries, but most of these activities may adversely affect a worker over time. In addition to physical health, physically demanding work can also alter the mental state, which may lead to decreased productivity, poor judgement, inattentiveness, poor work quality, job dissatisfaction, and ultimately more accidents and injuries (Abdelhamid and Everett 2002). The transportation construction environment is generally more hazardous than most other work environments since the work is often conducted along active roadways and it involves the use of heavy equipment, dangerous tools, and hazardous materials, all of which increase the potential for accidents and injuries (Roja et al. 2006; Xing et al. 2020). In general, monitoring and controlling physical demand is of paramount importance to sustain productivity without undermining workers' safety and health (Meerding et al. 2005).

Recent advancements in Physiological Status Monitoring (PSM) have made it possible to measure physiological metrics of construction workers in real time. Several studies in the literature reported that PSM devices have the potential to be applied in construction sites to monitor physiological metrics with acceptable levels of error (Gatti, Schneider, and Migliaccio 2014; Hwang et al. 2016). Among the physiological metrics, heart rate is identified as a reliable indicator of physical demand and workload, and therefore, is widely used in physical demand measurement in the literature (Hsu et al. 2008; Zhu et al. 2017). For example, Hwang and Lee used a type of wristband PSM device to measure the heart rate of 19 construction workers to assess their physical demand over time. In this study, they used the percentage of heart rate reserve (%HRR) as a measure of physical demand. The study results indicated that the physical demand of construction workers significantly varies over time. Accordingly, they concluded that physical demand of construction workers need to be continuously monitored during workers' ongoing work to avoid safety and health risks (Hwang and Lee 2017). In a similar study, using a wristband PSM device, Lee et al collected the heart rate data and subjective perceived fatigue level of 12 workers over the period oftwo days. They applied heart rate reserve (%HRR) thresholds to identify the fatigue index for each of the time intervals. The correlation analysis indicated statistically meaningful correlation between the fatigue index and self-reported fatigue level (Lee, Lee, and Brogmus 2023).

Despite the contribution of these studies in assessing physical demand of construction activities, limited research exists on assessment of physical demand with respect to physiological acceptable thresholds and boundaries. Moreover, there is limited research assessing physical demand in transportation construction. The present study is conducted to address these existing gaps.

Research Objectives and Methodology

The objective of this study is to apply a non-intrusive system to monitor and assess the physical demand of transportation construction workers. Specifically, this study analyses the physical demand variations across different transportation construction activities performed during a bridge rehabilitation project with respect to acceptable physiological thresholds and boundaries. The Zephyr Bioharness was used to collect the physiological metrics of the workers such as heart rate, breathing rate, heart rate variability, and acceleration within the working hours. Although this device is originally designed to optimize the performance of professional athletes, several studies reported excellent reliability of using this device to measure heart rate and breathing rate (Lee, Lin, et al. 2017; Lee, Seto, et al. 2017; Pillsbury et al. 2020). The device is worn around the chest with the electrodes picking up the electrical signals from the heart. The collected physiological data can be transmitted to a smartphone, a fitness watch, or a computer for real time display or offline analysis (Zephyr 2016). Real time monitoring of the physiological metrics can enable workers or supervisors to prevent the exceedance of physiological thresholds to ensure safety and wellbeing of the workers. However, in the present study, offline analysis was performed since the objective of the paper is to evaluate the physical demand in bridge rehabilitation, and therefore the authors did not want to interfere with the common practice of the construction work.

Photographs with timestamps were also recorded to document the physical activities being performed to correspond to the heartrates recorded. Five bridge maintenance workers volunteered and gave consent to record their physiological metrics using a Bioharness while performing various construction and maintenance tasks. These volunteers were professional construction workers employed by the City and County of Denver. The experiment protocol for the study was reviewed and approved by the Institutional Review Board (IRB) at the University of Colorado Denver. Data collection was performed while the workers completed a bridge expansion joint replacement project from August 30, 2022 to September 2, 2022 in Denver, Colorado. Weather conditions were generally sunny and warm, with ambient temperatures ranging from 17 to 28 degrees Celsius over the course of the four days. The PSM harnesses were issued to the volunteers each morning, at the outset of the full day of construction activity. Upon completion of the work day, PMS harnesses were removed with log the data from individually numbered data puck. Volunteers received the same numbered puck during all data collection periods in order to ensure anonymity of data and allow effective collection of data across different activities. The schedule of construction and maintenance tasks are shown in Table 1. The demographic characteristics of participants are shown in Table 2.

Table 1

Schedule of performed construction activities in each day

Day	Performed Activities
1	Concrete demolishing and jackhammer operation
2	Concrete demolishing and jackhammer operation
3	Rebar work, expansion joint placement, and welding
4	Concrete placement and installing the expansion joint gland (joint seal)

The percentage of Heart Rate Reserve (%HRR) is used as a measure of physical demand. This method normalizes the original value of heart rate by the heart rate reserve of each individual (differences between maximum and minimum heart rate of each individual) to provide a relative measurement of physical demands, as shown in equation (1). This method measures the minimum heart rate at rest as a level with no physical intensity and demand. The Maximum heart rate is calculated based on the age of each individual (Tanaka, Monahan, and Seals 2001) as shown in equation (2) and Table 2. It should be noted that the collected heart rate data of different individuals are not comparable if not normalized as heart rate depends on the physical characteristics of each individual such as body size, age, and fitness levels. However, %HRR provides a relative metric that can measure the excessive cardiovascular load due to physical exertion by offsetting each individual's characteristics (Hwang and Lee 2017; Wu and Wang 2002).

$$\%HRR = \frac{HR - HR_{Rest}}{HR_{Max} - HR_{Rest}} \quad (1)$$

$$HR_{Max} = 208 - 0.7 \times Age \quad (2)$$

Where: $\%HRR$ is the percentage of Heart Rate Reserve; HR is the heart rate and is measured in units of beats/minute, HR_{Rest} is heart rate at rest; HR_{Max} is the maximum heart rate as shown in equation (2).

Table 2

Demographic characteristics of participants

articipant Number	Age	Veight (Kg)	Ieight (cm)	HR_{Rest} (bpm)	HR_{Max} (bpm)	BMI (kg/m^2)
1	28	77.1	175	51	188.4	25.1
2	36	113.4	160	64	182.8	44.3
3	33	115.6	188	63	184.9	32.7
4	33	92.5	180	53	184.9	28.4
5	39	90.7	180	62	180.7	28

Table 3

%HRR *Zones, thresholds, description, and respective suggestions**

%HRR Zones	%HRR Range	Description	Suggestions
Sedentary	0%-20%	Activities that have little movements and a low energy requirement (MET < 1.6)	An intensity that can be sustained over 60 minutes
Light	20%-40%	Activities that do not cause a noticeable change in breathing rate (1.6 < MET < 3)	An intensity that can be sustained over 60 minutes
Moderate	40%-60%	Activities that can be conducted whilst maintaining a conversation uninterrupted (3 < MET < 6)	An intensity that may last 30 to 60 minutes
Vigorous	60%-85%	Activities in which a conversation generally cannot be maintained uninterrupted (6 < MET < 9)	An intensity that may last up to 30 minutes
High	85%-100%	Activities that have a very high energy requirement (> 9 MET)	An intensity that generally cannot be maintained for longer than 10 minutes

*Adapted from (Norton et al. 2010)

For this study, the authors adopted the Norton et al. categories of physical activity intensity (Norton, Norton, and Sadgrove 2010) to evaluate the worker's exposure to cardiovascular overload and overexertion. Norton et al. categorized the physical activity intensity based on objective measures such as %HRR, metabolic equivalent (MET), and subjective measures such as Borg rating of perceived exertion scale. This method classifies the intensity of physical activity into five categories including sedentary, light, moderate, vigorous, and high. Moreover, based on the literature, they specify safety suggestions for each of these categories. HRR thresholds, description, and respective suggestions are shown in Table 3. The aforementioned heart rate zones are used to investigate the variations of physical demands during a working day. It should be noted that workers' safety and health risks depend on both the physical demand and the duration of such intensity (Hwang and Lee 2017). To evaluate the overall physical demand of daily construction activities, average %HRR over the daily working hours is calculated. According to the literature, an average daily %HRR over %30 is considered as having a "high" cardiovascular load during an eight hour working day (Coenen et al. 2018; Gupta et al. 2014; Wu and Wang 2002).

Results and Discussion

Visualizations of the results show that the workers have similar trends and patterns of %HRR over the working hours, as shown in Figure 1. For example, the results show approximately 50% reduction in %HRR of each individual during the break times from 12:00 until 13:00. A comparison of timestamp photographs to the visual analysis of the collected data confirmed that %HRR is a good indication of the intensity of the physical activity. While general %HRR trends track across participants over time, %HRR for individual workers can vary at any point in time depending on the activity being performed; In other words, the workers %HRR can differently respond to same or similar work tasks compared to others. Discrete spikes in %HRR for individuals are observable when individuals are performing intensive tasks such as running the jackhammer or lifting heavy construction materials. Based on the heart %HRR zones defined in the methodology, workers' exposure to cardiovascular overload were analyzed. The results of the first two days show that concrete demolishing and jackhammer operation require a high physical demand over all the duration of working hours. The third day required lower physical demand compared to the first two days. Based on the results, the most demanding task performed on the third day was the placement and adjustment of the expansion joint from 13:00 until 15:15, as shown in Figure 1. In the fourth day concrete placement was performed which required the lowest physical demand compared to the other days. In the fourth day, the most demanding task was installing the expansion joint gland (joint seal) from 14:45 until 15:15 after the concrete hardened. Figure 2 shows cumulative time spent in a given %HRR zone. Only one participant (participant four) spent a recordable amount of time in the high %HRR zone. This occurred on the last day while trying to install the expansion joint gland (joint seal). It is also worth noting that the cumulative time of work intensity varied by worker. In other words, participants varied in which days they worked hardest. Despite the variations of physical demand among different individuals, day by day comparison of the results shows that the first two days had the highest portions of %HRR in the moderate and vigorous zones indicating higher demand of the performed activities. On average, all of the construction workers stayed in 0% to 60% of HRR zone over 80% of working hours, as shown in figure 2.

Figure 1. %HRR participants in each day

To have a better understanding of overall demand, average %HRR over the daily working hours was calculated for each of the participants in each day, as shown in Figure 3. It is possible to observe that the participant rank of average daily %HRR changes order most days. Nevertheless, average daily %HRR for all participants remains in the 30%-50% range, with the exception of participant one on the fourth day. According to the literature, this range of %HRR can be considered as having a “high” cardiovascular load during an eight hour working day (Coenen et al. 2018; Gupta et al. 2014; Wu and Wang 2002).

The %HRR results show that participants 1 to 4 had multiple occurrences of %HRR over 40% that were sustained over 30 minutes on days 1 to 3. This indicates excessive cardiovascular overload according to Norton et al. categories of physical activity intensity, as discussed in the methodology section. Therefore, interventions need to be made to reduce these workers' physical demands. This highlights the importance of continuous measurement of heart rate during workers' ongoing work and balancing workloads in order to prevent cardiovascular overload. To this end, a flexible work-rest schedule with frequent short breaks can be considered to avoid consistent high physical demand. Moreover, physiological demanding tasks need to be distributed as evenly as possible throughout the working days to prevent over even distribution of workload throughout different working days to prevent excessive physical demands at a certain day.

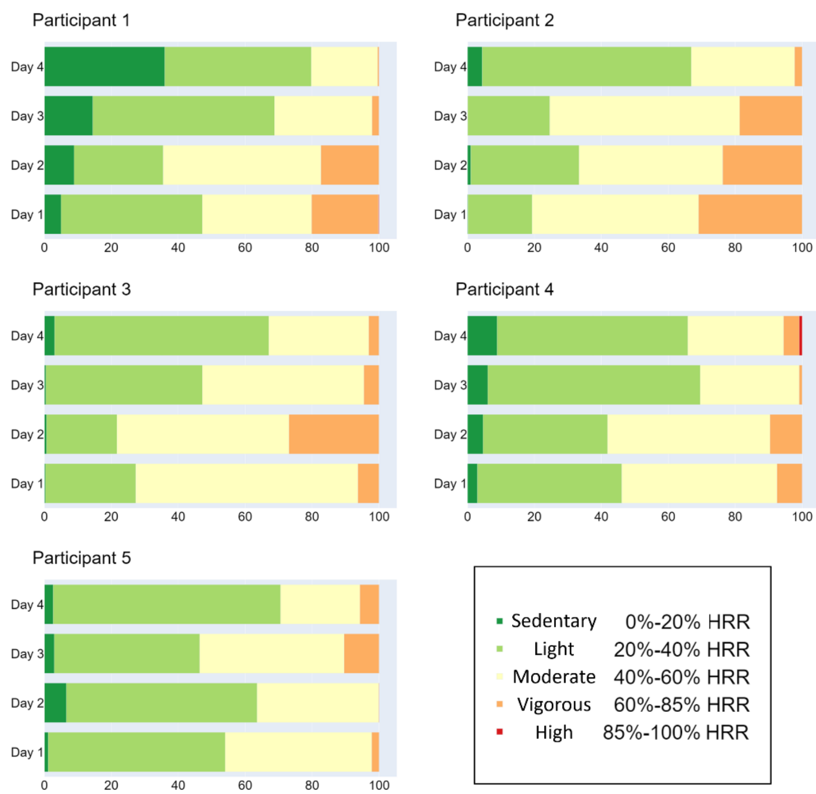

Figure 2. %HRR Zones for each of participants in each day

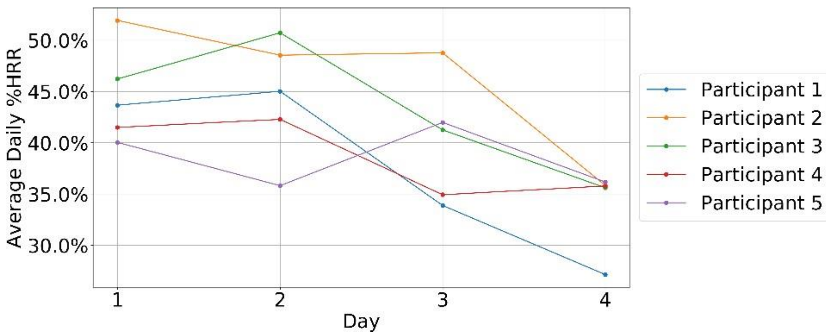

Figure 3. Average daily %HRR of participants in each day

Summary & Conclusions

The present study applied a non-intrusive system to monitor and assess the physical demand of transportation construction workers using the percentage of Heart Rate Reserve (%HRR) as a measure. To this end, five bridge maintenance workers volunteered and gave consent to record their physiological metrics while performing various construction and maintenance tasks on a bridge rehabilitation project. The results of the case study showed that workers' physical demands can be highly variable during working hours depending on the performed construction activity. Based on the results, bridge maintenance work can be classified as high demanding occupation with average daily %HRR over 30 percent. Moreover, the analysis of demand variations across different transportation construction activity showed that concrete demolishing and jackhammer operation caused the highest (spikes in) %HRR levels and also resulted in the highest average daily among other activities. According to the results, the majority of the participants had multiple occurrences of %HRR over 40% that were sustained over 30 minutes on days one to three which can be regarded as excessive cardiovascular overload. This highlights the importance of continuous measurement of heart rate during workers' ongoing work and balancing workloads in order to prevent overexertion. By recording and monitoring the physical demand of construction activities and comparing worker data to established benchmarks of physiological thresholds, companies will be better able to 1) assess individual health performance and risks, 2) compare the strenuousness of various construction activities, and 3) use such data to establish best practices for task assignment and durations under a variety of conditions to maximize the health and safety of their workers. This study can be extended to evaluate the effect of different work-rest schedules on reduction of cardiovascular overload.

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