Field Use of Physiological Status Monitoring (PSM) to Identify Construction Workers' Physiologically Acceptable Bounds and Heart Rate Zones

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ABSTRACT

The construction environment affects workers' physical responses as well as individual and crew-level performance. Previous research has analyzed the relationship between worker performance and severe environments. This paper reports initial results and a process for establishing reliable, physiologically acceptable bounds and heart rate (HR) zones for construction workers. Five workers at the same building jobsite accepted to wear a Physiological Status Monitoring (PSM) system for several days while at work. HR data were collected to identify physiologically acceptable bounds and HR zones as practical threshold-based guidelines in construction. Since HR is affected by various external variables, daily video recordings and weather data were also collected and used to explain results.

INTRODUCTION

The reliability of Physiological Status Monitoring (PSM) technology for monitoring physiological status of construction workforce during demanding activities has been previously tested (Gatti et al. 2011). This technology has also shown the ability to link worker's productivity with heart rate (HR) (Gatti et al. 2013b) as well as to automatize ergonomic analysis and task-level activity analysis of workers through data fusion (Cheng et al. 2013a; Cheng et al. 2013b). These early studies supported the claim that PSM technology could help achieve social sustainability on construction projects by providing a quantifiable assessment of construction workforce safety and well-being (Gatti et al. 2013a). To this end, the relationship between worker performance and severe environments has been recently studied. Among other independent variables, HR data have been used to predict the workers' subjective rating of perceived exertion (RPE) (Chan et al. 2013) and to determine optimized work-rest regimens and work paces by applying the Predicted Heat Strain (PHS) model (Rowlinson and Jia 2013). Previous efforts to study construction work physiology has identified in HR one of the best indicators when measuring physiological load (Jorgensen et al. 1999; Abdelhamid and Everett 2002). When HR exceeds acceptable levels, it is more likely there will be physical failure, which could lead to lost time from injury and, consequently, losses in safety and productivity (Brouha 1967; Saha et al. 1979; Buller and Karis 2007). Brouha (1967) used a 110 beats·min^{-1} HR threshold to judge potential overexertion and fatigue of workers in general without referring to any specific industrial setting, which is a threshold "based on an average young (25 year old) adult male" (Abdelhamid and Everett, 2002; pp.436). Abdelhamid and Everett (2002) also suggested correcting this threshold by taking into consideration influencing factors, including worker age. Therefore, this threshold is not particularly useful for construction workers considering their wide range of ages and labor intensive work loads. This paper reports preliminary results of a study that attempted to address these gaps by collecting field PSM data and using them to outline a process for determining construction workers' acceptable bounds and HR zones. This paper also assesses the feasibility using PSM technology in the field.

METHODOLOGY

Type of Data Collected. Many types of data were collected with the goal of evaluating the impact of workers' physiological status and jobsite environmental factors on worker behavior and performance. During the monitoring, the following data were collected: subjects' HR and breathing rate (BR), global positioning system (GPS) data, jobsite environmental data, subjects' perceived level of fatigue, sampled video recordings, and crew-level weekly average productivity rates. For the purpose of this paper, only HR, weather data and video recordings were analyzed and are described.

- *PSM Data:* Previous studies found that the Zepyhr BioHarness™ PSM provided a high level of accuracy and is suitable for monitoring construction activities (Gatti et al. 2011; Gatti et al. 2013b). Therefore, the latest version of this PSM was used for the HR data collection, the Zephyr BioHarness™ 3.
- *Jobsite Environmental Data*: A wireless weather station (Vantage Pro2 Plus™ Weather Station, Davis Instruments) was installed in the midsection of the tower crane. The wireless console, which received temperature, rainfall, and relative humidity data transmitted from the weather station, was installed inside a trailer.
- *Videos:* Researchers used a digital camcorder to record workers' activities. Daily, each subject was video observed three times during five minutes respectively: (1) early in the morning, (2) late in the morning, and (3) in the afternoon.

Data Collection Methods. Five workers were enrolled as subjects in the study. Each subject wore the PSM unit for 3 to 15 days while working at a jobsite for the construction of a five-story mixed use building in Seattle. A workday began at 7:00am with a short stretching session. To promote coordination, each foreman repeated aloud his crew's day tasks during this session. Then, subjects returned to the trailer to prepare a pre-task plan and discuss it with the general foreman. Workers performed their daily tasks over three sessions between breaks: 7:30am–10:00am (session 1), 10:15am–12:00pm (session 2), and 12:30pm–3:00pm (session 3). Sometimes, subjects worked until 4:00pm to complete critical tasks or to compensate for rain delays. They usually had a light breakfast during their mid-morning break and a lunch at noon.

Data were collected during two separate periods. Initially, researchers monitored a carpenter and three laborers from July 29 to August 8 (warm/hot season;

measured average temperature: 65.3°F). Later, two carpenters and one of the laborers were invited to participate in a second monitoring period (October 14 to 18; cool/cold season; measured average temperature: 49.9°F). Since concrete placement was completed in October, the authors could not collect data during the coldest season in Seattle (December to February). In addition, two subjects did not participate to the second observation period because they were mostly scheduled to work on non-value added tasks or were not going to perform labor-intensive work. Instead, another carpenter was enrolled into the study to take part in the second period of monitoring. *Table 1* provides descriptive statistics for the subjects (age range: 27 to 40 years old; height range: 175 to 190 cm; weight: 84 to 104 kg). Predicted max HRs, body fat percentages (%FAT), and body mass index (BMI) were estimated based on each subject's age, height, and weight. *Table 2* includes values of %FAT and BMI side by side with subjects' HR data.

Table 1. Subject Descriptive Statistics.

Subject Number	Predicted Max HR (bpm)[1]	Task	Data Collected		
			Data (hours)	Warm/Hot Season	Cool/Cold Season
1	182	Formwork(Carpenter)	120	Y	Y
2	187	Formwork	85	Y	Y
3	171	Formwork(Carpenter)	27	N	Y
4	189	Cleaning deck	59	Y	N
5	187	Layout; Pour Watch	48	Y	N

[1]HRmax = 203.7 / (1 + exp(0.033 × (age − 104.3))) for men (Wohlfart and Farazdaghi 2003).

Data Collection Issues. PSM data were sometimes lost due to a malfunction of a PSM unit. Most common issues included a malfunctioning device with short battery life and rare instances of the HR logging signal being temporarily cut off. Other data collection issues included: (a) smaller data sets when a worker had to leave the jobsite early; (b) lack of data when a worker was absent; (c) lack of data when a worker refused to wear the PSM device on a very hot day; and (d) loss of data due to faulty device set-up process. At the end, data were acquired for at least three days from all subjects.

DATA ANALYSIS

Data Segmentation. The researchers used the scheduled work breaks to divide the HR data into three sessions for data analysis. This decision was not arbitrary, as it is known that resting and food intake/digestion during breaks has an effect on HR. To make each session comparable with the others, only the last 90 minutes of data before the next break were analyzed. This decision was based on adapting all sessions to the smaller session between the morning and the lunch breaks (Session 2). Therefore, Session 1 was composed of data collected between 8:30 and 10:00 am, and Session 3 was composed of data in the last 90 minutes before the closing of the daily schedule.

Outliers. Because the HR data with normal healthy individuals are normally distributed, we performed Grubbs' test to detect and remove outliers from the data sets (Grubbs and Beck 1972): (1) we drew time-series plots of HR data; (2.a.) if the suspicious outlier showed obvious direction toward the high peak or the low peak, a one-tailed Grubbs' test was performed (alpha level = 0.05); (2.b.) if both the high and low peaks were observed as suspicious outliers, a two-tailed Grubbs' test was performed (alpha level = 0.05) (*Figure 1*). The Outlier R-package 'outliers' was used to perform this task (Komsta 2011). This study removed outliers instead of replacing by interpolation, as this approach is adequate for studies on average values.

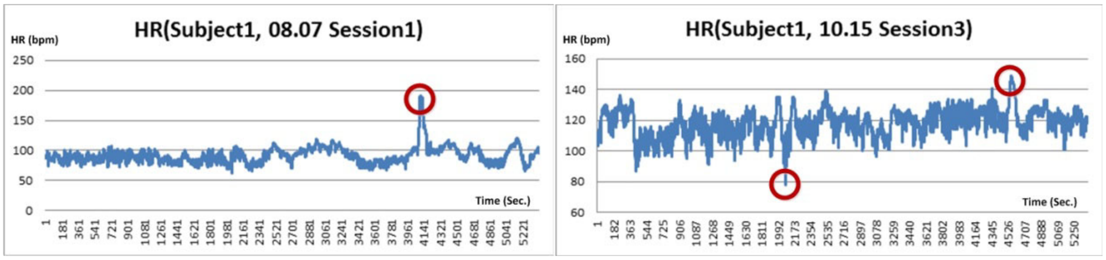

Figure 1. One-tailed Grubbs' Test versus Two-tailed Grubbs' Test.

Analysis of Average HR Values. The analysis showed that the average measured HR was higher in session 2 for all subjects. Subject 1 was selected to represent the graphical analysis of data because there were no missing data during the 15 consecutive experiment days (*Figure 2*). This subject has a higher average HR on Monday and Friday, compared with the average HRs for the other days of the week (*Figure 2*). A review of the self-reported tasks for Session 2 showed that most of the subjects were assigned major tasks, including work that involved column or shear wall form fabrication, installation, or stripping (*Figure 3*). Videos were also used to confirm the accuracy of self-reported tasks. Since the available camcorder did not allow to timestamps at the second level, it was not possible to synchronize the HR data feeds with the videos to micro-analyze if specific actions or postures had influenced HR values.

Physiologically Acceptable Bounds. For the purpose of this study, a worker's physiological status is defined as acceptable if his HR range values are within a range that is expected to reduce the worker's exposure to cardiovascular overload or overexertion. A study has introduced an approach for identifying acceptable bounds for HR and BR based on warfighters' PSM data (Buller and Karis 2007). This study calculated the maximum and minimum acceptable HR bounds on the basis of the maximum HR obtained when a subject ran on the running mill in the laboratory environment and the minimum HR obtained when a subject was observed in a sitting position by equations (1) and (2).

$$HeartRate_{min} = HeartRate_{min\ sitting} - (2 \times HeartRate_{SD\ sitting}) \quad (1)$$

$$HeartRate_{max} = HeartRate_{max\ running} + (2 \times HeartRate_{SD\ running}) \quad (2)$$

In our study, minimum HR values were determined for the subjects from resting HR in a sitting position in the trailer at the beginning of a work day. However, it would not be meaningful to determine maximum HR through laboratory experiments on a treadmill for construction industry purposes. Instead, the authors have decided to use HR readings from an actual construction working environment to determine maximum acceptable values. Therefore, the second equation has been modified to calculate the physiologically acceptable range for the individual level of a construction worker as in the following equations (3) and (4).

$$HeartRate_{min} = HeartRate_{min\ resting} - (2 \times HeartRate_{SD\ resting}) \quad (3)$$

$$HeartRate_{max} = HeartRate_{max\ working} + (2 \times HeartRate_{SD\ working}) \quad (4)$$

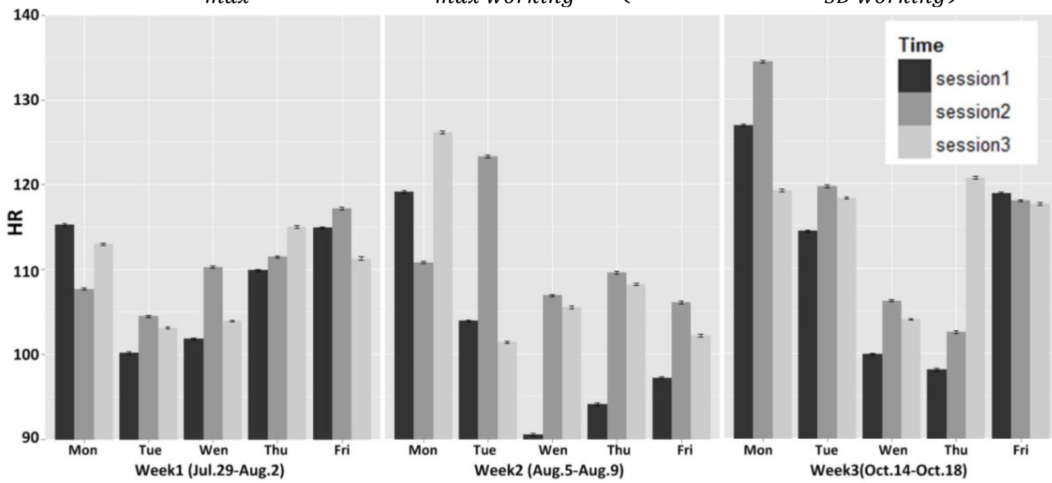

Figure 2. Average Heart Rates of Subject 1.

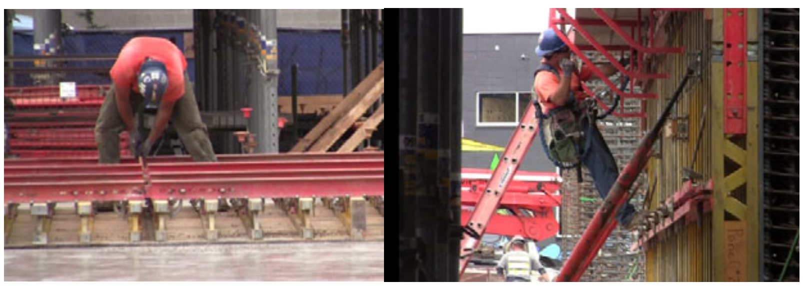

Figure 3. Subjects' Major Activities in Session 2 (10:30am-12:00pm).

Based on the modified formula, the physiologically acceptable bounds for each subject are summarized in *Table 2*. This table shows that, for individual subjects, the maximum acceptable HR could be higher (or lower) than the maximum HR for the average individual in their age/gender category. The identified process allows for this customization of the acceptable bounds.

Heart Rate Zones. Based on the target HR(THR) zone calculation, following the Karvonen methods (Karvonen 1957), the zones are classified into 100–90%, 90–80%, 80–70%, 70–60%, and 60–50% levels of HR reserve (HRR). The following equation (5) is Karvonen's formula for the THR zone.

$$THR = \left((HR_{max} - HR_{rest}) \times \%\ intensity\right) + HR_{rest} \quad (5)$$

However, these HR zones were developed to determine the THR range to optimize benefits from exercising and training in athletes. Furthermore, the HRR is determined by using the predicted maximum HR minus the average resting HR. Since we have the individually measured maximum HR using PSM, we used it to determine HR zones for each construction worker rather than the predicted HR. In addition, we used qualitative emotional descriptors for each zone, adapting them from Edwards and Robinson (2006). Therefore, we can assume that a worker who stays in the red zone (Zone 5) or the distress zone (Zone 4) for a long time period will potentially start to feel disconnected and unproductive in his task (*Table 3*). This association between quantitative HR information and qualitative descriptors is expected to be particularly useful to guide management in assigning tasks to workers.

Table 2. Physiologically Acceptable Bounds.

#	BMI[1]	%Fat[2]	Predicted HRmax (bpm)	Measured Resting HR (bpm)			Measured Working HR (bpm)			Acceptable Range (bpm)		Measured vs. Predicted HRmax (%)
				Mean	SD	Min	Mean	SD	Max	Min	Max	
1	27.4	25.7	182	71	3.9	62	134	11.6	174	54	197	95.6%
2	25.8	21.6	187	77	6.8	61	124	18.9	176	47	214	94.1%
3	26.9	28.2	171	63	3.5	56	90	13.6	160	49	187	93.6%
4	30.4	26.2	189	102	7.4	82	139	23.6	190	67	237	100.0%
5	25.1	21.1	187	80	4.2	69	105	13.9	175	61	203	93.6%

[1]BMI = Weight(kg)/ $(\text{Height(m)})^2$ (Clark et al. 2002).
[2]%Fat= (1.20 x BMI) + (0.23 x Age) – (10.8 x gender)-5.4, where the value of gender is equal to 1 for males, while 0 for females (Deurenberg et al. 1991).

Table 3. Emotional Heart Zones Based on Physiological Status.

Zone	%Intensity	Emotional zone	Feeling In Zone
5	90-100%	Red	Out of Control, frantic, total panic, disconnected, emergency
4	80-90%	Distress	Worried, anxious, angry, scattered, fearful, reactive
3	70-80%	Performance	Focused, in the flow, “in my element”, positive stress
2	60-70%	Productivity	High concentration, effective, prolific
1	50-60%	Safe	Meditative, relaxed, affirming, regenerative, comfortable, compassionate, peaceful
Adapted from Karvonen (1957)		Adapted from Edwards and Robinson (2006)	

Data from subjects 1 and 3 from October 14th were selected to discuss the acceptable bounds and the HR zone developed because, on this day, these two subjects performed similar tasks as carpenters. The range of HRs zones has been calculated with the modified Karvonen’s formula. The range of Zone 3 was from 143.1 to 153.4 bpm for Subject 1 and from 130.9 to 140.6 bpm for Subject 3. From this calculation, the threshold value to judge unsafe stress levels was 153 bpm for Subject 1 and 141 bpm for Subject 3. If the construction workers’ HRs were over each of their own threshold values, the potential of high mental stress level with the worries and frantic feelings will be increased. When applying the developed physiological acceptable bounds and HR zones on the individual level, Subject 1 was exposed to a higher chance of lost time due to injury or overexertion as compared with Subject 3 (*Table 4*). As shown in *Table 4*, it was found that the HR zone value which is estimated by the Karvonen’s formula is a stricter guideline than the physiological acceptable bounds estimated in section 3.2. This information could be used by the project management staff to modify the working schedule of subject 1 to improve his occupational safety and health.

Table 4. Percentages of Exceeding Physiologically Acceptable Bounds and Threshold Heart Rate Zone.

	Subject1		Subject3	
Day 11-Oct. 14- Monday	**% of exceeding acceptable bound[1]**	**% of exceeding performance heart rate zone**	**% of exceeding acceptable bound[1]**	**% of exceeding performance heart rate zone**
Session1	0%	3.0%	0%	0%
Session2	0%	3.4%	0%	0%
Session3	0%	1.1%	0%	0%

[1]Physiologically Acceptable Heart Rate Rage (Table 2)

CONCLUSION

In conclusion, the subjects' measured HR averages in Session 2 were usually higher than those of the other sessions. This could be because the time allotted for work in Session 2 was relatively shorter. The subject possibly had to finish the assigned task with a higher level of pressure during this short session, which suggests hourly assigned workload affects cardiac load. In addition, the weekly data analysis represents higher average HRs on Monday and Friday, as compared with other weekdays. The higher HR values on Fridays could be an indicator of an increasing cumulative fatigue level at the end of a workweek.

This study has preliminarily evaluated the feasibility of using PSM technology as a worker-inspection system that could indicate overexertion, prevent potential worker injury, illnesses, and cardiovascular overload. Using this system, a field safety manager would be able to identify in real-time workers who consistently carried cardiovascular loads by comparing current HR data with worker-specific acceptable physiological bounds and HR zones. When any of the workers showed signs of heightened HR or abnormalities over thresholds in the PSM system, the safety or project manager could check on the conditions of the workers and ensure adequate recovery time to return to threshold HR. Furthermore, this system would allow project management staff to reschedule workers' assigned tasks or assign an additional laborer to the team to guarantee achievement of the target productivity without overloading specific workers. Apart from measuring the HR data, PSM systems are able to record additional parameters, including core temperatures, activity and posture. Further studies should be designed, and conducted to fully capture worker's physical stress, behavior and performance in the construction field.

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