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Physiological Metrics Across Construction Activity

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Safety management and occupational health are essential for construction work. Several studies examine the extent to which physical activity impacts the health and safety of construction workers. To date, however, few studies directly assess the impact of construction activities. This research analyzes physiological and environmental data to explore the impact of construction activity on individual workers, under a range of ambient conditions. Vital signs and physical indicators including heart rate, breathing rate, core temperature, physiological load, mechanical load and posture were collected from a relatively homogeneous set of US Air Force Academy cadets while performing four different construction activities. Results suggest average physiological measures (i.e. mean Heart Rate, Breathing Rate etc.) statistically vary by individual even for individuals similar in age, health, and fitness. Despite individual distinctions, statistical trends and patterns are observable across construction activities. Specifically, the results demonstrate that concrete and asphalt placement are generally more physically demanding, followed by, heavy equipment operation and surveying activities respectively. In addition, the ambient variable, Heat Index, plays a significant role and merits future research. The primary contribution of the research is to demonstrate a method for monitoring and assessing discrete physiological metrics across individuals as well as construction activity.
Key Words: Construction Worker Health, Physiological Metrics, Safety, Physiological status monitoring technology

Introduction

Many construction activities require extensive physical labor over extended periods, sometimes with exposure to adverse weather conditions. Construction, in general, is a labor intensive process where workers are subjected to unusual work postures, heavy weight lifting, and a range of work postures (Hartmann and Fleischer 2005). Injuries from construction activity can be immediate or cumulative over time. Physical stress and strain can lead to decreased work productivity, inattentiveness, or inability to make wise decisions. Construction productivity is generally measured as the number of hours of work required to complete a specified work product (Jang et al., 2011). While productivity is not directly measured in this research, it is well-documented that the typical, demanding workload of construction can take a toll on both the mental and physical health of a worker. Furthermore, continuous depression and dissatisfaction from a worksite can result in unwanted accidents and more injuries (Abdelhamid and Everett 2002). Construction workers are exposed to ergonomic hazards, which include dynamic movement, various unusual postures, pulling and lifting loads (Hartmann and Fleischer 2005). They are at risk to develop musculoskeletal disorders (Engholm and Holmström 2005).

A number of studies focused on analyzing the impact of construction work on workers using physiological indicators such as heart rate, body temperature, and blood oxygen level (Abdelhamid and Everett 2002; Buller et al. 2010; Kirk and Sullman 2001). For example, Abdelhamid and Everett (2002) collected oxygen consumption and heart rate data to determine the performance of 100 construction workers doing moderate to heavy work. The data showed that the average oxygen uptake was 0.82 L/min (± 0.22 L/min) and the average heartbeat was 108 beats/min (± 17 beat) min). Measurements were compared to standard guidelines for acceptable levels of physical performance for specific industrial environments. Results indicated that 20-40% of the workers regularly exceeded recommended thresholds for manual work, thereby making the workers more prone to inattentiveness, decreased productivity, poor judgment, accidents, and injuries. Several research works studied the factors affecting heat stress (Rowlinson et al. 2014; Yi et al. 2016; Yi and Chan 2015). For example, Rowlinson et al. (2014) studied factors affecting climatic heat stress and identified three ways of reducing heat stress in construction sites: (1) control of climatic heat stress exposure through the use of an action-triggering threshold system, (2) control of continuous work time with mandatory work-rest routine, and (3) allow workers to follow self-pace regimes. Other studies considered additional indicators such as posture to evaluate the health hazards among construction workers (Roja et al. 2006; Tak et al. 2011). For example, Roja et al. (2006) conducted a study on workers from the heavy civil industry which included ten road construction and maintenance workers and ten pavers who belonged from the age group 20-60 years. The study measured the physical demands of road construction work and estimated muscle fatigue. Average metabolic energy consumption for road construction and repair work was recorded as 8.1± 1.5 kcal/min, and 7.2 ± 1.1 kcal/min for paving respectively. Their findings documented that road construction work requires extreme manual labor, compulsive working posture, and continuous arm and leg movements. In the same study, they monitored the workers' heart rate, posture and muscle tone for a week and suggested that work-related musculoskeletal problems could be likely for these workers. Several studies applied physical monitoring systems (PMS) for the purpose of physiological monitoring, environmental sensing, proximity detection and location tracking analysis on construction workers (Aryal, Ghahramani, and Becerik-Gerber 2017; Awolusi, Marks, and Hallowell 2018; Lee and Migliaccio 2016; Wang et al. 2017; Yu et al. 2017). For example, Gatti et al. (2014) investigated the validation of PMSs for construction based on two physiological parameters including heart rate and breathing rate. Results indicated that PMS data can be used to identify and correlate physical strain, task level, productivity, and safe-unsafe behavior of construction workers.

Although the aforementioned studies had significant contributions in examining the extent to which physical activity impacts the health and safety of construction workers, there are limited studies that focused on monitoring and collecting physiological data of workers across different construction activities under a range of ambient conditions. Moreover, former studies have primarily been limited to one or more physical indicators of the construction workers. The present research focuses on the analysis of multiple physical indicators across four construction activities.

Research Objectives and Methodology

The objective of this research is to develop and advance a system that analyzes physiological and environmental data to explore the impact of construction activity on individual workers, under a range of ambient conditions. For this research, the system was applied to a relatively homogenous set of workers, in this case, a set of ten US Air Force Academy (USAFA) cadets comprised of 8 males and 2 females, who each performed four distinct construction activities under similar, relatively controlled, conditions. International Review Board protocols for research involving humans were completed under the supervision of USAFA. During the study period, volunteers were following similar food and sleep regimens. All the volunteers were within the age range of 20-22. The following metrics were analyzed: heart rate, breathing rate, core temperature, mechanical load, physiological load, and posture. Metric descriptions are provided in Table 1, based on research and available manufacturer information (Zephyr 2013).

Table 1

Metrics

Metric	Description	Units	Notes
Heart Rate	It is measured as the number of heart beats per minute.	Heartbeats per minute	The measure of Heart rate is analyzed from the 250Hz Echocardiogram (ECG) data
Breathing Rate	It is measured as the number of breaths per minute.	Breathing per minute	The sensors inside the zephyr puck detect breathing by the expansion and contraction of our torso.
Posture	It is measured as the change of angle of any individual in comparison with gravity.	Degree from the vertical position.	When an individual is standing straight the measurement is zero. Forward and backward leaning accounts for positive and negative values.
Core Temperature	The core temperature is estimated based on the heart rate.	Degree Centigrade	The accuracy of this estimate and have also demonstrated that such a computational measurement can indicate physical stress before an individual reaches an unhealthy state (Buller and Hoyt 2008).

Volunteers' physiological characteristics were monitored during four construction activities. Table 2 defines these activities based on USAFA's FERL handbook descriptions ("Civil Engineering Practices - Field Engineering Cadet Handbook," 2017).

Table 2

Construction Activities

Activity	Description
Concrete Placement (C)	Prepare a site, set framework and reinforcement, place concrete, and take samples and perform slump test.
Heavy Equipment (HE)	Operate construction equipment including an excavator, scraper, bulldozer, loader, and paving machine.
Surveying (S)	Use total station to measure distance and horizontal/vertical angles. Layout a calculated location for concrete slab pour and use measuring techniques to plot land data.
Asphalt Paving (A)	Place a section of road using approximately 20 tons of asphalt.

The PMS device used for this study was the Zephyr BioHarness, an off-the-shelf product capable of remote physiological monitoring and location tracer without hindering the flexibility and freedom of the individual (Zephyr 2013, 2016). To retrieve the recorded data from PMS devices, and to analyze the physiological status for each volunteer, "Omnisense" software was used (Zephyr 2016). To this end, individual weight, height, age, and fitness levels of the volunteers were entered into the software. Based on the collected data, the software generated spreadsheets including, heart rate, breathing rate, posture, core temperature, and Heart Rate Confidence (HRC) for each of the volunteers. HRC is calculated based on electrocardiogram noise and worn detection. The threshold for accepting data was based on HRC of 80% or higher, based on the recommendation of Zephyr's representative. Lower HRC levels suggest the data is unreliable based on the faulty collection. This indicator is then used to remove the noisy data. After the data collection phase, software R was used to perform statistical analyses in 5 steps: (1) filter the noisy data based on HRC; (2) aggregate one-second interval data to one-minute interval data; (3) add morning and afternoon weather, temperature, humidity level, and heat index using local station data; (4) apply a Linear Mixed Effect Model (LMM) to analyze the effect and statistical significance of the independent variables including heat index and activity on the physiological metrics such as heart rate, breathing rate, posture, and core temperature per individual and construction activity; and (5) compare data and identify general and observable patterns.

Model Development

Multivariable linear regression is predominantly used to model the relationships among two or more explanatory variables and a response variable by fitting a linear equation to the observed data. For the collected data, there are repeated observations over time for an individual which cannot be assumed to be independent. An appropriate way to model such repeated measures data across time is the use of the linear mixed-effects model. The Linear Mixed Effect Model (LMM) comprises both fixed effects and random effects. The random-effects take care of the correlation between the repeated observations. For this study, the goal was to determine the effect of the independent variables such as gender, heat index, activity level and activity on the metrics. The LMM, therefore, can be written as shown in Equation 1.

$$Y_{ij} = \beta_0 + \beta_1 gender + \beta_2 H.I + \beta_3 A.L + \beta_4 A1 + \beta_5 A2 + \beta_6 A3 + \beta_7 A4 + b_i + \epsilon_{ij} \tag{1}$$

Where: Y_{ij} is the value of the response for the jth replication for ith individual; A1, A2, A3, and A4 are activity 1 to 4, respectively, and can have the value of 1 if the volunteer does the corresponding activity, and otherwise 0; gender is 1 for male and 0 for female; H. I is Heat Index; A. L is Activity Level; b_i is individual specific random effect for the ith individual; and ϵ_{ij} is the error (residual).
Likelihood Ratio Test (LRT) was used to determine if an outcome was statistically different from other outcomes. If a significant difference between activity outcomes was found, a pairwise comparison (t-test) was then used. To adjust raw p-values when testing various hypotheses, a Bonferroni correction (Dunn 1961) was used.

Results and Discussion

This research analyzed unique data sets to explore statistical relationships and observable patterns for physiological metrics variables as measured in construction workers of similar in fitness, age, and experience, performing four distinct construction activities. Violin plots representing the distribution of heart rate, breathing rate, core temperature, and posture across the four activities are shown in Figure 1. Violin plots visualize the distribution of the data and present a vertically symmetric probability distribution of the response variable as estimated from the data. These results indicate that concrete placement is the most physically demanding activity for all volunteers.

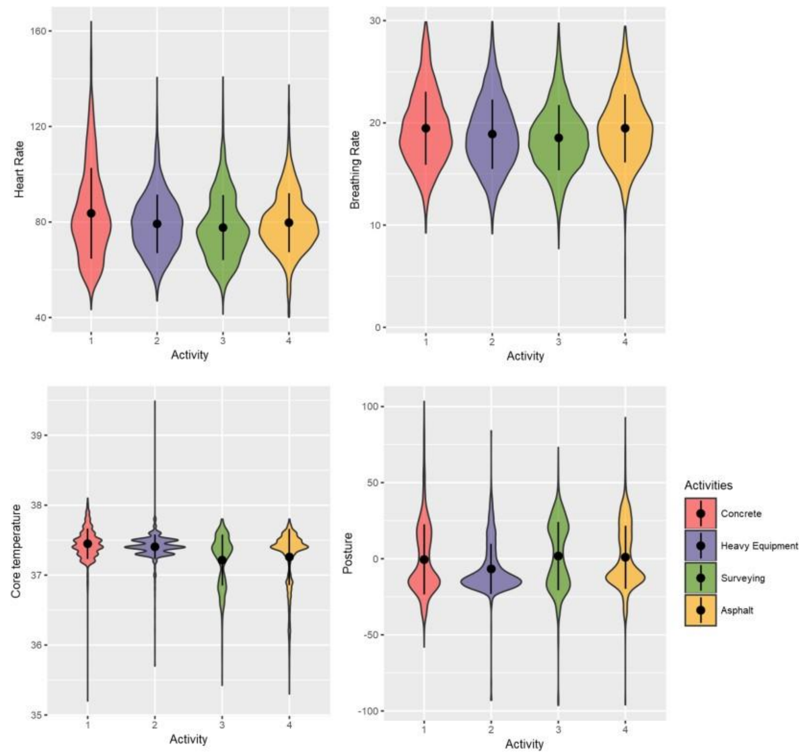

Figure 1. Violin plot showing the distribution of heart rate, breathing rate, core temperature, and posture across the four activities

To test for statistical differences t-test was performed for the heart rate, breathing rate, core temperature, and posture data across all 10 volunteers. The p-values indicate that: (1) heat index, activity level and activity are significantly associated with heart rate ($p \leq 0.05$), but gender is not significantly associated ($p > 0.05$). (2) heat index, activity level and activity are significantly associated with breathing rate ($p \leq 0.05$), but gender is not significantly associated ($p > 0.05$). (3) activity is significantly associated with core temperature ($p \leq 0.05$). (4) heat index, activity level and activity are significantly associated with posture ($p \leq 0.05$), but gender is not significantly associated ($p > 0.05$).

Pairwise comparisons between the different activities were performed to investigate which activities lead to significantly different heart rates, breathing rates, core temperature, and posture. The pairwise comparisons indicate that: (1) concrete-heavy equipment, concrete-surveying, heavy equipment-surveying, heavy equipment-asphalt result in statistically distinct heart rate profiles; (2) concrete-surveying, heavy equipment-surveying, surveying-asphalt result in statistically distinct breathing rate profiles from one another; (3) concrete- heavy equipment, concrete-surveying, concrete- asphalt, heavy equipment-surveying, and surveying-asphalt result in statistically distinct posture profiles; and (4) concrete-surveying, concrete-asphalt, heavy equipment-surveying, heavy equipment-asphalt, surveying-asphalt result in statistically distinct core temperature profiles from one another with the core temperature profiles during surveying and asphalt being the most distinct. Moreover, results suggest that heat index also affects the physiological metrics of individuals when performing construction activities.

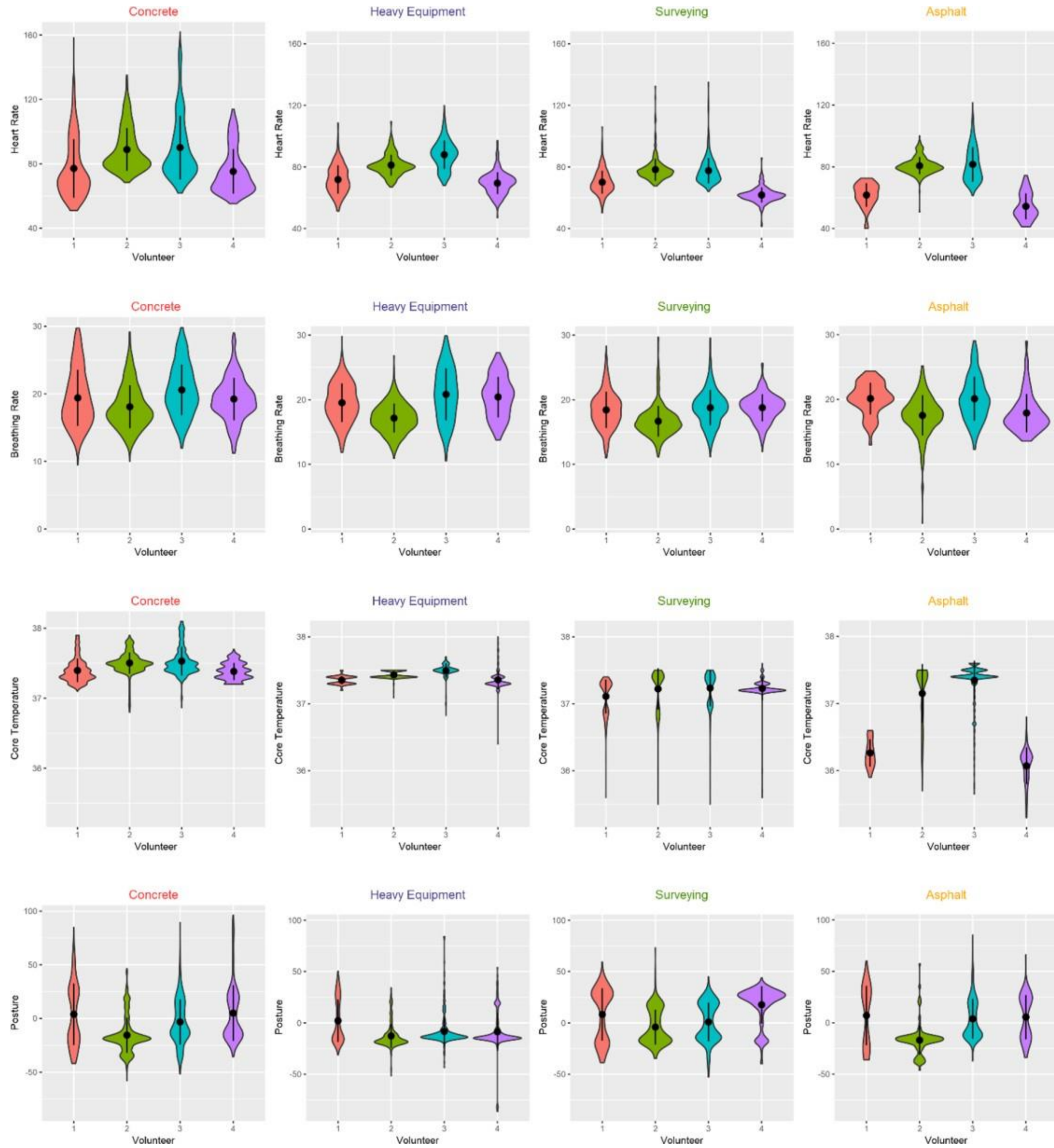

Figure 2. Violin plot showing the distribution of heart rate, breathing rate, core temperature, and posture for volunteers 1,2,3,4 across the four activities

In addition to the full analysis of the 10 volunteers, a focused analysis of the data from four volunteers who were in the same group was performed to minimize the role of external variables (such as weather, time of day, specific tasks performed etc.). Specifically, volunteers 1, 2, 3 and 4 were all working under the same climatic conditions and synchronously performing the same construction activities. Moreover, volunteers 1,2,3, and 4 were all male. Figure 2. shows the violin plots for each metric for the four volunteers performing concrete, heavy equipment, surveying, and asphalt activities to visually compare individual differences and patterns. A more in-depth look at the four volunteers performing construction activities concurrently confirms the results, suggesting that the research data collection and analysis method is capable of correctly identifying patterns for the impact of construction activities on construction workers. In particular, a general trend exists demonstrating that the mean heart rate for certain individuals (volunteers 2 and 3) is greater than others (volunteer 1 and 4) across all activities, but that patterns of the impacts of construction activity persist despite these individual differences. Similarly, Figure 2 shows that the mean posture metric for volunteers 1 and 4 is greater than volunteers 2 and 3 across all activities. In contrast, operating heavy equipment results in a posture that is the most reclined for nearly all volunteers.

Such results suggest that the studied metrics and methods are effective at assessing the impact of construction activities on individuals' physiological health. Furthermore, the study shows that it is possible to independently compare discrete physiological metrics across individuals performing activities under various weather conditions. In short, the research serves to highlight the significant opportunity to use the proposed research methods to study construction worker health and productivity in future studies.

While the longitudinal data from only four volunteers are based on a limited sample size, the similarity in conditions makes this data potential less confounded. Furthermore, the large number of data points collected for each volunteer still enables statistical comparison between and among metrics. In short, when heart rate is compared for the four volunteers (Figure 2), there is a clear pattern showing that heart rates for volunteers 1 and 4 are consistently lesser, on average, compared to volunteers 2 and 3. We can conclude that heart rate, in general, is higher for volunteers 2 and 3 irrespective of activity type. However, this general trend is shifted up or down based on the activity (although less so for Asphalt), suggesting that while individuals have different physiological norms, construction activities may impact distinct individuals in a similar manner, albeit, potentially, to differing extents. For example, the heart rates of all four volunteers are lower, on average, for surveying. Also, the heart rates reach a much higher value for concrete compared to other activities. Similar patterns are noticed for breathing rate and core temperature.

Finally, pairwise comparisons between the different activities were performed for the four volunteers to investigate which activities lead to significant differences. While perhaps not generalizable, results from pairwise comparisons p-values indicate: (1) all pairs of activities except asphalt and concrete yield significantly different heart rates; (2) all pairs of activities except surveying yield significantly different breathing rates. (3) all pairs of activities yield significantly different core temperatures. (4) asphalt-concrete and asphalt-surveying have similar posture and heavy equipment yields the most significant difference in posture.

Future Work

The present research provides a potentially transformative model for supporting the occupational health of construction workers and motivates future research in the area. In future work, additional methods, such as mutual information from information theory, will be applied to evaluate the impact and influence of independent variables on physiological metrics to provide a more thorough analysis. Moreover, there is a need for future research on the impact of working environments on workers due to the variety in types of construction projects. For example, in highway infrastructure projects, workers are exposed to the risk of injury from the movement of construction vehicles and equipment within the work zones, as well as from passing motor vehicle traffic. Therefore, the working condition in this type of project is expected to increase the stress levels in workers. Finally, the current research can be expanded to collect more data on different activities from different types of construction projects. Using pattern recognition methods such as machine learning algorithms, the collected data can be used to predict or assess when health or performance thresholds are about to be reached or exceeded. In particular, such research will assist managers in scheduling workers to maximize productivity and minimize workplace injuries under extreme weather or working conditions. Moreover, these data can be used to establish indicators and real-time warning systems to help minimize potential physical harm to construction workers.

Summary & Conclusions

This study presented the development of a new system that uses physiological and environmental data to explore the impact of construction activities on individual workers, under a range of ambient conditions. The system was applied to a relatively homogenous set of workers, in this case, a set of ten US Air Force Academy (USAFA) cadets comprised of 8 males and 2 females, who each performed four distinct construction activities under similar, relatively controlled, conditions. Vital signs and physical indicators including heart rate, breathing rate, core temperature, physiological load, mechanical load and posture were collected and analyzed. To this end, software R was used to perform statistical analyses in 5 steps: (1) filter the noisy data based on HRC; (2) aggregate one-second interval data to one-minute interval data; (3) add morning and afternoon weather, temperature, humidity level, and heat index using local station data; (4) apply a Linear Mixed Effect Model (LMM) to analyze the effect and statistical significance of the independent variables on the physiological metrics; and (5) compare data and identify general and observable patterns. Research analysis suggests that heat index and construction activities have a measurable effect on the physiological metrics of individuals with similar physical characteristics. Specifically, results indicate that among the four different construction activities studied, concrete and asphalt paving are more physically demanding activities as compared to operating heavy equipment and surveying activities. Notably, looking at four volunteers working under similar climatic conditions revealed similar statistical and observable patterns for physiological metrics across construction activities. The results of this study suggest that such a research method yields statistically significant patterns and is capable of documenting the effects of construction activity as well as ambient conditions on individual construction worker health and performance. Such research will be critical in establishing physiological thresholds for construction workers while performing a range of activities under various climatic conditions.

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