ASSESSING PHYSICAL STRAIN IN CONSTRUCTION WORKFORCE: A FIRST STEP FOR IMPROVING SAFETY AND PRODUCTIVITY MANAGEMENT

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Abstract

Safety issues impact construction workforce and industry, for example by generating extra costs and delays. Achieving planned levels of productivity is crucial for the overall success of a construction project. Despite improvements in equipment and workplace ergonomics, the construction industry is still characterized by physically demanding activities and stressful environments. Excessive physical strain on the workers leads to decreased productivity, inattentiveness, poor quality work, accidents, and injuries. Therefore, a Physical Demand Monitoring System (PDMS) able to assess physical strain through a combined analysis of workers' physiological parameters (e.g., heart rate) and environmental conditions (e.g., temperature) may be an important step towards better safety and productivity management. In previous studies of physiological demands in construction the instrumentation hindered the workers' activities. However, now less invasive technologies are available for this purpose. The scope of this project is to establish the framework of a PDMS able to operate in real construction situations.

KEYWORDS: heart rate, physical strain, safety, productivity.

INTRODUCTION

Despite recent improvements in construction equipment and workplace ergonomics, the construction industry is still characterized by physically demanding activities often performed in a harsh environment. According to several researchers (Abdelhamid & Everett, 1999; Abdelhamid & Everett, 2002; P. Åstrand, Rodahl, Dahl, & Strømme, 2003; Bouchard & Trudeau, 2008; Brouha, 1967; Garet et al., 2005), there is a reciprocal relationship between physically demanding work, safety and productivity. A "decrease in performance due to fatigue is widely accepted, but no agreement has been reached in trying to quantify this decrease" (Abdelhamid & Everett, 1999). "In the work environment, EE (*i.e., Energy Expenditure*) measurement can help evaluate task intensity, shift duration, number and length of breaks or to establish a threshold of fitness needed for a return to work" (Bouchard & Trudeau, 2008). "Physical demanding work can lead to physical fatigue, which may lead to decreased productivity and motivation, inattentiveness, poor judgment, poor quality work, job dissatisfaction, accident and injuries" (Abdelhamid & Everett, 2002). Furthermore, according to Mathiassen (1993) a continuous exposure to excessive level of physical strain can increase the risk of developing musculoskeletal or cardiovascular disorders. Hence, the measure of physical strain for construction activities is a crucial issue in managing productivity and preserving the workforce's health and safety.

Since the beginning of the twentieth century numerous studies have been conducted to assess physical demands for different trades and occupations. Several authors focused their attention on workers in light and heavy manufacture industry, teachers and lifeguards (Durnin & Passmore, 1967; Myrtek, Fichtler, Strittmatter, & Brügner, 1999). Other studies focused on fishing activities (Biswas & Samanta, 2006; Rodahl, Vokac, Fugelli, Vaage, & Maehlum, 1974), iron and steel industry (Kang, Woo, & Shin, 2007), miners (Palenciano, Gonzalez, Santullano, Rodriguez, & Montoliu, 1996), firefighters (Elsner & Kolkhorst, 2008; Richmond, Rayson, Wilkinson, Carter, & Blacker, 2008), choker setters (Kirk & Sullman, 2001), and farmers (Perkiö-Mäkelä & Hentilä, 2005). Few studies on construction workers are available (Abdelhamid & Everett, 1999; Abdelhamid & Everett, 2002; I. Åstrand, 1967; Turpin-Legendre & Meyer, 2003). However, most of these studies have severe limitations. In some studies the measuring equipment was clumsy and uncomfortable; therefore it interfered with the subject's normal activities or it could not be worn for the whole work day (Abdelhamid & Everett, 1999; Abdelhamid & Everett, 2002; I. Åstrand, 1967; Elsner & Kolkhorst, 2008; Richmond et al., 2008). In other studies the techniques selected to evaluate the physical demands were suitable for only a small number of subjects or they could not monitor the subjects continuously (Myrtek et al., 1999; Perkiö-Mäkelä & Hentilä, 2005; Rodahl et al., 1974; Turpin-Legendre & Meyer, 2003).

Hence, the aim of this paper is to delineate a set of ideas that provides the basis for the development of a PDMS able to implement non-invasive technologies to continuously assess construction worker's physical strain. First, is given a brief description of the research project for which this paper represents the first step. Then, the features and issues of the system are described. A short summary of methods used to assess physiological strain is presented, followed by the description of the selected method. Finally, the devices that will be utilized are presented.

IMPROVING SAFETY AND PRODUCTIVITY MANAGEMENT

Dealing with construction safety and productivity is still a key problem in construction and the measurement of workers' physical strain may provide a way to address it. Thus, the goal of this paper is to develop a PDMS to measure the workforce's physical strain. But, this paper is the first part of a wider research project focused on studying the relationship between physical strain, safety and productivity. Explaining the successive phases of the larger project falls outside the scope of this paper, but for the purpose of understanding the PDMS development a brief description is given.

Research Hypotheses

The general scheme is that physical strain, productivity and safety are related. In particular, the focus is on the idea that an increase in physical strain may negatively affect safety behaviors and productivity. Furthermore, the collected data will allow analyzing the relationship between productivity and safety (see Figure 1). To assess productivity and safety two sampling techniques will be implemented: productivity ratings for productivity (Oglesby, Parker, & Howell, 1989) and behavior sampling for safety (Petersen, 1971; Tarrants, 1980). The measure of the physical strain is described in a following section.

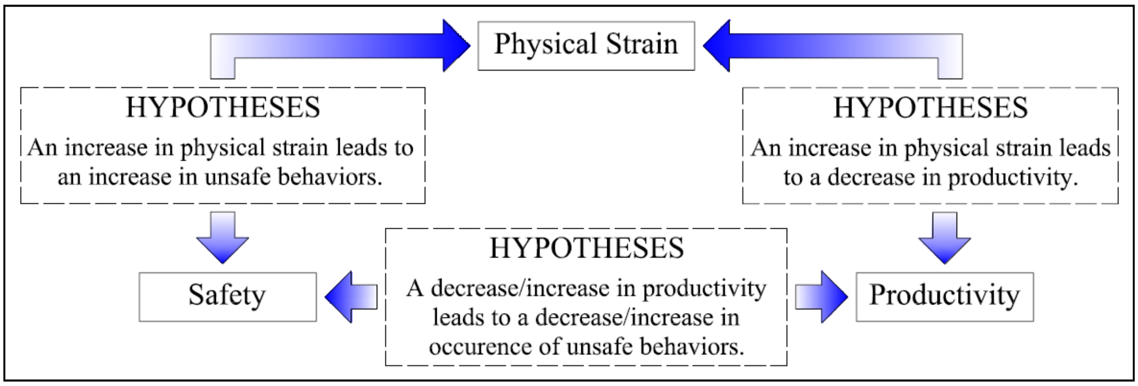

Figure 1: Research Hypotheses

PROBLEM DESCRIPTION

The main purpose of the PDMS is to continuously monitor workers performing routine activities within a construction site to obtain an estimation of physical strain. There are a few main concepts that have guided the design of the monitoring system. Hence, this system should be able:

- To monitor physiological parameters of construction workers individually and record data in real time to allow a timely analysis of the physiological parameters. This fact implies that each worker has to be equipped with a Physical Status Monitoring device (PSM);
- To collect environmental information (e.g. air temperature, humidity, wind velocity) as control variables for the physiological parameters. Hence, an environmental station has to be installed within the construction site; and
- To transmit the information to a central station to allow informed decision making by management personnel.

Obviously, the system's features are also influenced by characteristics, requirements and constraints of construction sites and activities. Therefore, the system should:

- Not provide potential harm to workers (i.e., using the system should not increase risk of harm to construction workers or its benefits should overcome any potential risk);
- Not hamper any construction activity (i.e., using the system should not interfere with other systems on the construction site, such as remote-controlled cranes or other equipment);
- Not include PSM devices that are obtrusive, uncomfortable and/or hinder standard workers activities (e.g. since workers will need to carry individual PSM devices to collect physiological parameters during the entire workday, they would need to be lightweight);
- Require little training to learn how to use the system;

- Be able to use for monitoring large groups;
- Allow the data collection without external involvement to avoid the presence of non construction personnel within the site; and
- Be reliable even in a harsh environment (i.e., construction sites may be a challenging environment for technological devices because of the often concurrent action of dust, humidity, and vibrations).

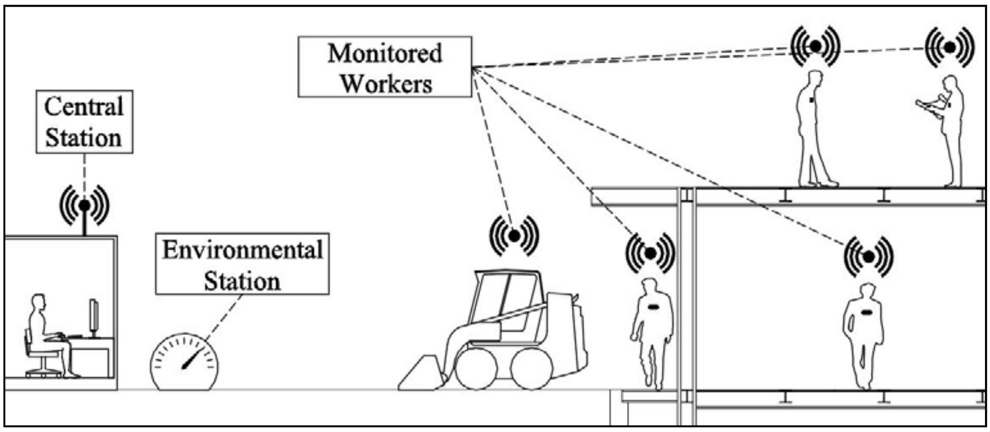

Figure 2: Schematic Description of the System

PHYSIOLOGICAL STRAIN ESTIMATION

The importance of physiological strain estimation is evidenced by the great number of techniques and methods that have been developed, such as the Rating of Perceived Exertion method (RPE) (Borg, 1982) and the measurement of oxygen consumption (Abdelhamid & Everett, 1999; Abdelhamid & Everett, 2002). In particular, Heart Rate (HR) monitoring and motion sensors are taken in consideration.

Estimation of physical strain through HR has been successfully used and validated in several field studies (Abdelhamid & Everett, 1999; Abdelhamid & Everett, 2002; Aminoff, Smolander, Korhonen, & Louhevaara, 1998; Beynon, Burke, Doran, & Nevill, 2000; Bussmann, Hartgerink, Van Der Woude, & Stam, 2000; Bussmann, Berg-Emons, Angulo, Stijnen, & Stam, 2004; Hui, Ng, Yeung, & Hui-Chan, 2001; Myrtek et al., 1999; Nevala, Holopainen, Kinnunen, & Hänninen, 2003; Richmond et al., 2008; Turpin-Legendre & Meyer, 2003). Kirk and Sullman (2001) concluded that “heart rate indices can be used as an effective means of determining the physiological strain of subjects in applied field situations”. Moreover, this technique does not present any characteristics that might prevent its implementation in the proposed system. Minute-by-minute HR data can be collected with individual devices that are lightweight, unobtrusive and comfortable. Inexpensive commercial HR devices are already being used in harsh environments (e.g., athletes in training, soldiers and firefighters on duty). HR devices are user-friendly and able to communicate wirelessly with a central monitoring station using several protocols (e.g., Bluetooth, radio). Hence, monitoring of HR was selected for the PDMS.

Motion Sensors (i.e., accelerometers) are instruments able to detect total or partial body displacement. According to (Melanson & Freedson, 1996) the theoretical basis for their utilization is that body acceleration is directly proportional to muscular forces.

Accelerometers have been used in many studies (Bussmann et al., 2000; Bussmann et al., 2004), but not all activities (e.g., carry a load or walk on a gradient) can be detected. They can be effective on well defined activities (e.g., walking), but in complex, construction-type activities, they are not reliable. Hence, even if this method is feasible for a construction site, it should not be implemented alone because of its low accuracy.

Absolute and Relative Assessment

Different subjects react to the same workload in different ways. An easy workload for one person can be exhausting for someone else. This difference is due to the fact that the relative intensity of the task is related to innate (e.g., gender, size, muscle mass, age) and current characteristics of the subject (e.g., fitness level, capacity of adaptation to environmental conditions, hydration status). Hence, absolute HR rate values can be quite meaningless. Instead, to give an estimation of the subject exertion, a relative index should be used. Thus, HR has to be expressed in relation with the subject's maximal HR and/or resting HR. Several HR indices have been developed and used in the estimation of the physiological strain. Here the index that will be implemented in the proposed system is briefly presented.

Relative heart rate at work (%HRR) is obtained by applying the formula (Rodahl, 1989):

$$\%HRR = [(HR_w - HR_{rest}) / (HR_{max} - HR_{rest})] \times 100$$

where:

- HR_w is the HR while the subject is working. HR_w is an average value calculated during a certain amount of time. According to the necessity to ensure timely decision for the proposed system, the time step will be 1 minute.
- HR_{rest} should be "the median value of the 6 hours of sleeping when HR values are lowest" (Garet et al., 2005). In some studies (Kirk & Sullman, 2001; Perkiö-Mäkelä & Hentilä, 2005) it was not possible, therefore less precise estimation of HR_{rest} were used. "Heart rate at rest was measured after 5 min of rest in the supine position" (Perkiö-Mäkelä & Hentilä, 2005). Hence, for the present purpose the method to HR_{rest} will be defined in accordance with the future subjects.
- HR_{max} is the maximal HR for the subject. This value can be obtained in several ways, such as during a cardiac stress test at maximal exertion, or using one of several prediction formulas, such as HR_{max}=220-Age. Cardiac stress tests are usually performed in laboratories under medical supervision for individual considered to be at high risk.

Environmental Conditions

The environmental conditions are a factor that can affect HR and increase physiological strain. In particular, an increase in heat stress results in an increase in HR, even during rest. According to P. Åstrand, Rodahl, Dahl, & Strømme (2003) HR not only responds rapidly to increases in ambient temperature, but it also tends to oscillate synchronously. Construction activities are mainly accomplished outdoors and workers are exposed to a wide range of ambient conditions. Thus, HR is a good indicator of physiological strain as it reflects both the effect of physical activity but also the strain provided by any environmental stress (Gertner, Israeli, & Cassuto, 1984). Hence, to take in consideration the environmental stress the WBGT index will be evaluated using an environmental station.

HR Monitoring Limitations

In literature it is possible to find several authors that stressed the limitations in using HR to assess physical strain (Abdelhamid & Everett, 2002; Aminoff et al., 1998; P. Åstrand et al., 2003; Bussmann et al., 2000). In fact, many factors may influence HR without affecting physical strain.

First, it is necessary to take into consideration factors that may alter the normal physiological processes that control HR, such as illnesses, medical devices, or medications. Hence, subjects affected by one or more of these issues may not be effectively monitored by the proposed system.

Even with the same level of workload, the use of small (i.e., arms) or large muscles (i.e., legs) affects the HR (Aminoff et al., 1998; Bussmann et al., 2000). "It is well established that heart rate is higher with arm work than with leg work at the same workload" (P. Åstrand et al., 2003). This fact may represent an important hindrance in the use of HR for construction activities that usually involves arms and legs. Nevertheless, according to P. Åstrand et al. (2003):

> Because most ordinary work operations involve a dynamic type of work with a rhythmic alteration between muscular contraction and relaxation, in which each period of work effort is rather brief, it appears that using recorded heart rate to estimate workload is acceptable even in many work situations involving arm work or the use of small muscle groups.

Furthermore, psychological factors are able to influence HR without affecting physical strain, such as stress, attitude (positive or negative), motivation, etc.. In literature it is possible to find several studies that address this issue (Yao et al., 2008; Veltman & Gaillard, 1998). It has been shown that mental workload may cause an increase in HR when a subject is resting or performing low levels of exertion. Thus it is sometimes difficult to differentiate between mental and physical workload influence on HR. However, the influence of mental workload noticeably decreases when HR is higher than 115 beats per min.

Consumption of food, coffee/energy drinks, alcohol and tobacco also can affect the HR. Also in this case the simple monitoring of HR alone cannot detect if HR is influenced by any of these other factors. Therefore, coupling the monitoring of HR and body displacements may increase the accuracy of the physiological strain estimation. Using sensors to measure movement complements HR monitoring, since it allows differentiation between increased HR caused by physical activity and that caused by other influences such as caffeine and stress (Myrtek et al., 1999; Rennie, Rowsell, Jebb, Holburn, & Wareham, 2000).

MEASURING EQUIPMENT

In this section, are presented the technological devices that are selected to be implemented in the PDMS.

Physical Status Monitor (PSM)

Two PSMs were selected, the BioHarness BT (Zephyr Technology Corporation, Annapolis, MD) and the EQ-01 (Hidalgo Ltd, Swavesey, UK). These PSM have been used in different scenarios, such as firefighter, soldiers, and athletes. In particular the EQ-01 is approved by US FDA and it has CE certification as a medical device (ISO 13485-2003). In Table 1 the main characteristics are presented. Both PSMs are lightweight devices that are worn around the chest on a fabric belt (see Figure 3 and 4). To guarantee the optimal positioning an additional shoulder strap is provided. They are comfortable, do not hinder the subject and can be used for several hours. Both PSM's can transmit live data or work as data logger. Their memory and battery are enough to collect data for a whole work day without interruption. Via Bluetooth, they can communicate directly with a PC or with other enabled devices (e.g., mobile phones, Bluetooth gateways) without interfering with other technologies that may be present in a construction site (e.g., crane's remote control). This feature gives a great flexibility in the development of the wireless communication system.

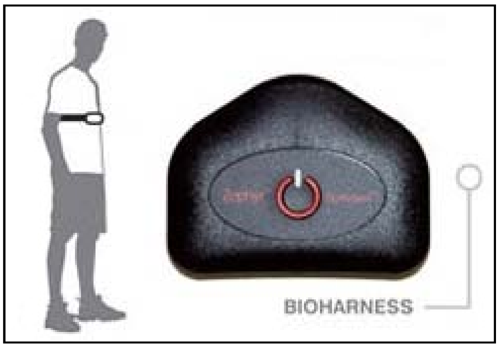

Table 1: PSMs' Features

Name	BioHarness BT	EQ-01
Dimension	80 x 40 x 15 mm	123 x 75 x 14 mm
Weight (without belt)	35 g	75 g
Parameters Monitored	heart rate, ECG, breathing rate and depth, skin temperature, 3D acceleration, and body orientation	Heat rate, ECG, breathing rate and depth, skin temperature, movement, and body orientation
Min Calculation Frequency	1 s (programmable)	15 s (programmable)

Environmental Station

Two environmental stations were selected, the QUESTemp 36 (Quest Technologies, Oconomowoc, WI) and the Testo 400 (Testo Inc., Sparta, NJ). These devices are currently used in industrial environment for heat stress monitoring and for indoor quality assessment. The monitored parameters are dry, wet and globe temperature, relative humidity, and air velocity. Their memory and battery are enough to collect data for a whole work day without interruption.

CONCLUSION AND FUTURE WORKS

This paper describes the general background and the set of ideas to provide a starting point for the development of a PDMS. This device aims to assess construction worker's physiological strain without interfering or hindering standard construction activities. The system's needed capabilities are presented and the combined use of HR and motion sensors is discussed as a method to measure physical strain. Two PSM systems and two environmental stations are identified for further analysis and their features are illustrated. Further research is needed to assess PDMS reliability in evaluating physical strain during standard construction activities.

This paper describes the first step of a wider research project focused on studying the relationships between physical strain, safety and productivity. Hence, the next research step is the implementation of the PDMS in a real construction sites to appraise these relationships. Furthermore, the proposed PDMS may be successfully applied outside the proposed scenario. For example, it can monitor the physiological conditions of workers in confined spaces (e.g., tanks, storage bins, and silos), in underground operations (e.g., mines, tunnels), or in extreme environments (e.g., extreme hot/cold temperature).

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