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An exploratory study of the relationship between construction workforce physical strain and task level productivity

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The monitoring of construction workforce physical strain can be a valuable management strategy in improving workforce productivity, safety, health, and quality of work. Nevertheless, clear relationships between workforce performance and physical strain have yet to be established. An exploratory investigation of the relationship between task level productivity and physical strain was conducted. Nine participants individually performed a four-hour simulated construction task while a wearable physiological status monitor continuously assessed their physiological condition. Heart rate, relative heart rate, and breathing rate were utilized as predictors of physical strain, and task level–single factor productivity was used as an index of productivity. Numerous regression models were generated using the collected data. This investigation initially unsuccessfully attempted to establish a relationship between physiological condition and productivity at the individual worker level. However, an analysis of the regression models showed that there is a relationship between productivity and either heart rate or relative heart rate at the group level, and that this relationship is parabolic. Breathing rate was proved to not be a significant predictor of productivity. Research results significantly improve understanding of the relationship between work physiology and task productivity. Researchers and practitioners may use the tested monitoring devices, analysis methods, and results to design further applied studies and to improve workforce productivity.

Keywords: Occupational health and safety, operations management, productivity, work physiology, workforce.

Introduction

Despite considerable improvements in construction methods, equipment, and tools, the construction industry is still characterized by physically demanding activities often performed outdoors under severe environmental conditions or in confined spaces with limited light and ventilation. In addition, as shown by many studies on ergonomic hazards in construction (Damlund *et al.*, 1986; Schneider and Susi, 1994; Hartmann and Fleischer, 2005), construction activities include forceful exertions, vibrations, heavy lifting and carrying, pushing and pulling, sudden loadings, awkward work postures, and repetitive motions. All these difficult conditions often add up to heavy physical strain due to the nature of construction work. Anecdotal evidence suggests that excessive physical strain can negatively affect work performance in terms of labour productivity, workers' safety and health, and quality of work. However, clear relationships between physical strain and workforce performance have yet to be determined. Therefore, analysing such relationships can be extremely beneficial in improving the construction industry's economic and social sustainability because it could suggest ways to improve efficiency and productivity

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while reducing the physical load on the construction workforce.

Numerous researchers from various disciplines debate the relationships between physical strain and work performance. By discussing approaches, methods, and techniques to improve construction productivity, Oglesby *et al.* (1989) found that excessive physical strain decreases a human's ability to work. In their research study on physiological demands for construction activities, Abdelhamid and Everett (1999, 2002) affirm that the decrease of work performance due to physical strain is a widely accepted concept. In their comprehensive monograph on work physiology, Astrand *et al.* (2003) list physical fatigue as one of the factors affecting work performance.

Other researchers indicate that excessive physical strain can be detrimental for workers' health and wellbeing. By analysing the influence of stresses due to industrial activities on workers' physiological status, Brouha affirms that evaluating the degree of workers' fatigue is the 'key to the solution of the problem of what a man can do safely' (Brouha, 1967, p. xiii). By studying an innovative method to estimate physical workload, Garet *et al.* (2005) support the concept that fatigue assessment is critical in preventing occupational risks.

An impressive literature can also be found on the relationship between physical strain and errors. In 2005, the Federal Aviation Administration stated that 'the entire workforce is susceptible to errors induced by fatigue' (Federal Aviation Administration, 2005, p. 16) in a manual for the management of aviation maintenance operators. By analysing data collected during 14 Russian space missions, Nechaev (2001) determined that crew members' errors and work and rest schedule intensity are correlated. Further, many accident causation theories affirm that excessive fatigue can increase the occurrence of human errors and, therefore, the occurrence of accidents and injuries. In the accident/incident theory, overload, ergonomic traps, and decision to err are the three main factors capable of fostering human errors with physical strain being listed among the factors causing overload (Goetsch, 2010). In Rasmussen's descriptive model of work behaviour (Rasmussen *et al.*, 1994), two main factors drive workers to perform unsafely: the tendency towards least effort that is mainly due to an increase in physical strain; and the management pressure for efficiency. In Shappell and Wiegmann's (1997) general human error model, accidents are due to a sequence of failures that can be categorized as unsafe supervision, unsafe conditions, and unsafe acts. On-duty physical strain is listed as one of the possible unsafe conditions.

Although the literature on physical strain and performance is extensive, research that clearly determines and quantifies the relationships between worker physical strain and performance has yet to be undertaken. Most of the presented theories are based on anecdotal evidence and/or heuristic approaches as clearly stated by the following authors:

> That a decrease in human's ability to work takes place is accepted as fact, but quantifying this decrease and placing limits on its acceptable levels have not been agreed upon. (Oglesby *et al.*, 1989, p. 242)

> The decrease in performance due to fatigue is widely accepted, but no agreement has been reached in trying to quantify this decrease or in setting acceptable limits for it. (Abdelhamid and Everett, 1999, p. 47)

Aim

Numerous studies have been published on assessing workforce physical strain, but there is no study analysing the relationship between physical strain and productivity. Thus, the aim of this study was to investigate, for the first time, the relationship between construction workforce physical strain and task level productivity. The relationship is analysed by applying regression analysis to the physiological and task level productivity data of nine participants performing a four-hour simulated construction task. Heart rate, relative heart rate, and breathing rate are used as predictors of physical strain; and task level–single factor productivity (i.e. productivity equal unit of completed work over labour period) is used as the measure of productivity. Data are analysed at both the individual worker level and the group level.

Background

Physical strain monitoring

Numerous techniques and methods have been developed to assess physical strain by monitoring physiological parameters (e.g. oxygen consumption and motion sensors). According to the reviewed literature (i.e. over 30 studies evaluating occupational exertion for numerous occupations), the most used method for assessing physical strain in field studies is heart rate (HR) monitoring. In fact, 'heart rate indices can be used as an effective means of determining the physiological strain of subjects in applied field situations' (Kirk and Sullman, 2001, p. 397). Furthermore, HR is reliable in assessing overextension and fatigue (Muller, 1950). Finally, HR monitoring 'provides information on the amount of time spent in high-intensity activity, which may be useful for assessment of physical activity' (Ainslie *et al.*, 2003, p. 688). However, HR monitoring presents several limitations because HR can be affected by numerous factors other than physical activity (Aminoff *et al.*, 1998; Bussmann *et al.*, 2000; Ainslie *et al.*, 2003; Astrand *et al.*, 2003). Thus, some considerations are necessary to effectively implement HR monitoring to assess physical strain.

Muscles types

Even at the same workload, HR differs according to whether small muscle groups (i.e. arms) or large muscle groups (i.e. legs) are used (Aminoff *et al.*, 1998; Bussmann *et al.*, 2000; Astrand *et al.*, 2003). This could prevent the use of HR monitoring for physical strain assessment due to the fact that construction activities involve arm and/leg movements. However,

> 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. (Astrand *et al.*, 2003, p. 511)

Environmental conditions

A change in ambient temperature and/or humidity causes a change in HR even at rest. Moreover, HR not only is affected by changes in environmental temperature, but it also tends to fluctuate synchronously (Astrand *et al.*, 2003).

Emotional/mental activity

Several studies addressed the influence of factors such as positive or negative attitude and motivation on HR (Veltman and Gaillard, 1998; Hjortskov *et al.*, 2004; Yao *et al.*, 2008). Mental stress can trigger an increase in HR. However, its influence significantly decreases when HR is higher than 115 beats per minute.

Hydration

Murray (2007) affirmed that dehydration can greatly influence HR. 'Adequate drinking during exercise helps attenuate the reductions in blood volume, cardiac output, muscle blood flow, skin blood flow, the rise in core temperature, and the impairment in exercise performance that accompany dehydration' (Murray, 2007, p. 542S). Thus, adequate hydration must be guaranteed to effectively assess physical strain from HR.

Absolute and relative HR assessment

Reactions to workload depend on a person's characteristics, both innate (e.g. gender, size, muscle mass, age) and acquired (e.g. fitness level, heat acclimation status). Thus, absolute HR measurements may be meaningless if they do not take into consideration individual characteristics. To avoid this issue, a relative HR (RHR) can be expressed in relation to individual maximal HR (HRmax) and resting HR (HRrest) (Rodahl, 1989; Vitalis *et al.*, 1994):

$$\mathrm{RHR}[\%] = (\mathrm{HR} - \mathrm{HRrest})/(\mathrm{HRmax} - \mathrm{HRrest}) \times 100 \tag{1}$$

Other

Additional factors must be considered for a correct physical strain assessment. Illnesses, medical devices, or medications may alter the physiological reactions that control HR. Also, digestion, consumption of stimulants (e.g. coffee/energy drinks, alcohol, and tobacco) or depressive substances can affect the heart's activity regardless of the workload level.

Productivity monitoring

Whereas numerous definitions of productivity are available, productivity generally is defined as the ratio between the output of a production process over its inputs (Crawford and Vogl, 2006). Productivity definitions can be divided into two main categories: single factor productivity and multifactor (or total) productivity (Thomas and Mathews, 1986; Organisation of Economic Cooperation and Development, 2001; Crawford and Vogl, 2006). The difference rests on the fact that single factor productivity takes into consideration one input (e.g. number of workers or man-hours), while multifactor productivity considers two or more inputs (e.g. labour, materials, equipment, energy, and capital). Further, productivity can be calculated at task (e.g. steel erection), project (i.e. combination of two or more tasks), and industry levels (i.e. combination of two or more projects) (Chapman and Butry, 2007). Along with the numerous productivity definitions, several techniques for productivity assessment, evaluation, and tracking have been developed, such as the method productivity delay model (MPDM) (Adrian and Boyer, 1976); the construction industry institute method (Construction Industry Institute, 1990); the XYZ model (Chitester, 1992); the construction productivity metric system

(CPMS) (Park *et al.*, 2005); activity/work sampling techniques (Richardson, 1976; Thomas, 1981, 1991; Thomas and Daily, 1983; Thomas *et al.*, 1984; Liou and Borcherding, 1986; Oglesby *et al.*, 1989); time (or stopwatch) studies (Salvendy, 2001); and questionnaires and surveys (e.g. foreman delay survey and craftsman questionnaire sampling introduced respectively by Tucker *et al.* in 1982, and Chang and Borcherding in 1986). Therefore, the selection of how to define and assess productivity generally depends on two factors: the scope of the measure (e.g. benchmarking against competitors or assessing task performance) and the availability of data.

Physiological monitoring technology

Innovative devices designed to monitor physiological parameters in numerous field applications (e.g. remote healthcare, fire-fighters, soldiers, and athletes) are now available thanks to advances in miniaturized computing hardware, wearable biosensors, and wireless communication technologies. These devices, generally called physiological status monitors (PSMs) or wearable health-monitoring systems, are wireless systems designed to monitor users in an autonomous, remote, and unobtrusive manner (Pantelopoulos and Bourbakis, 2009). PSMs can be worn for several hours with no interruptions and without hampering users during either dynamic or static activities. The PSM selected to monitor the study participants is the BioHarness BT (BH-BT, Zephyr Technology Corporation, Annapolis, MD) (Table 1). In previous studies (Gatti *et al.*, 2011a, 2011b; Gatti, 2012), this PSM unit was compared against two other PSMs and was found to outperform them.

Experimental design

Participants

The experiments involved nine apparently healthy volunteers (five males and four females; age 20.9 ± 1.62 yr.; height 1.70 ± 0.08 m; mass 66.6 ± 7.2 kg) with little or no experience about construction site operations. The participants were informed about the potential risks of the study and signed a written informed consent before participating in the experiments. Further, the participants completed a physical activity questionnaire adapted from the PAR-Q (Canadian Society for Exercise Physiology, 2002) and a health history questionnaire to confirm that it was safe for them to perform moderate physical activity. Thus, participants with either a history of cardiovascular disease or other physical reasons preventing them from safely performing moderate physical activity were excluded.

Construction task

An indoor simulated construction task consisting of assembling a raised deck was adopted. In particular, the task was designed to not present a significant learning curve and to be accomplished by participants with little or no experience in construction.

Construction materials

The raised deck was made of concrete panels (20 × 41 × 5 cm; 7 kg) and adjustable plastic supports (Figure 1).

Laboratory settings

The laboratory was subdivided in three contiguous areas: the working area used by participants to perform the simulated construction task; the resting area used by participants to rest during pauses; and the monitoring area used to set up the monitoring devices. Further, the working area was subdivided into two flooring areas, in which the deck was assembled, and three storage areas, in which the construction materials were stored (storage area A and B for the supports, and storage area C for the panels) (Figure 2).

Assembling procedure

Participants performed the construction task according to the designed assembling procedure (Table 2). A flooring area was completed when seven rows of panels were assembled. Once a flooring area was

Table 1 BioHarness BT technical specifications (Zephyr Technology, 2009)

Dimensions	80 × 40 × 15 mm
Weight (without belt)	35 g
Shoulder strap	Over both shoulders, removable
Monitored bio-signals (sampling frequency/reporting frequency)	EKG (250 Hz /250 Hz); breathing rate (18 Hz /1 Hz); skin temperature (1 Hz / 1 Hz); and, 3D accelerations (50 Hz /50 Hz)
Derived bio-signals (source bio-signals/ reporting frequency)	Heart rate (EKG /1 Hz); and, body orientation (3D acc./1 Hz)

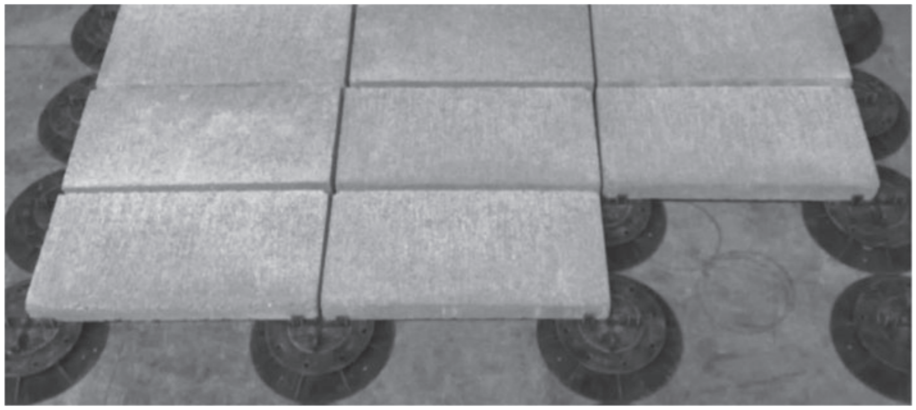

Figure 1 The raised deck

completed, participants assembled the deck on the other flooring area. In the meantime, a lab assistant removed the assembled deck and placed the removed materials in the storage areas. Thus, participants worked without interruption.

Working conditions
All participants but one, who participated twice, accomplished one experimental session. Further, participants performed one at a time and worked according to one of the following schedules:

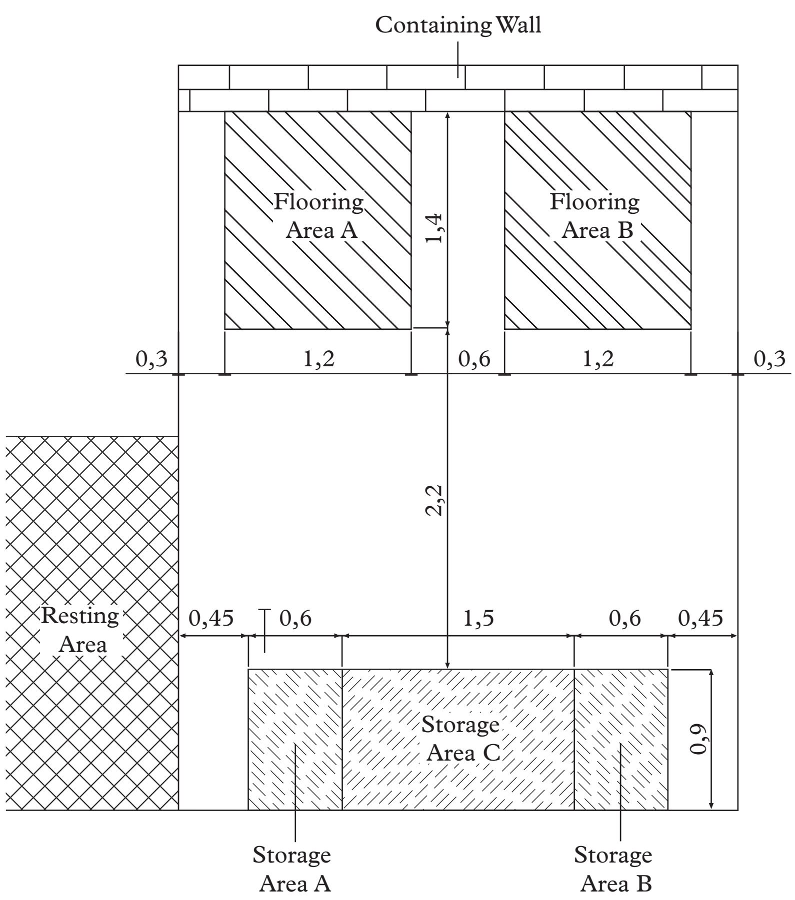

Figure 2 Working area subdivision (annotations in metres)

Table 2 Assembling procedure

Step	Action
1	Lift and carry 4 supports from the storage area A (or B) to the flooring area A (or B)
2	Place the supports in the flooring area A (or B)
3	Walk back to the storage area
4	Repeat the following actions (i.e., step 4.1, 4.2, and 4.3) three times to complete a row of panels (a row of tiles is made of four supports and three panels):
4.1	Lift and carry a panel from the storage area C (panels are piled up) to the flooring area A (or B)
4.2	Place the panel in the flooring area A (or B) on the prepared supports
4.3	Walk back to the storage area
5	Start again from step 1

- Schedule S1. Three male and four female participants accomplished four working periods (WPs; approx. 50 minutes each) and three mandatory pauses for a total experiment duration of four hours; and
- Schedule S2. Three male participants accomplished four WPs (approx. 110 minutes each) and one mandatory pause for a total experiment duration of four hours.

Participants were allowed to rehydrate as needed while working. Water bottles were provided in the work area. During the scheduled breaks, they could also eat some light snacks (granola bars and apples were provided). Further, participants were told to work continuously to simulate real construction workers' behaviour.

Participant preparation

Experimental guidelines (e.g. do not drink energy drinks, coffee, tea, or any beverage containing caffeine within two hours prior to the experiment) were provided to each participant in advance and repeated the day before the experiment. Upon arriving at the laboratory, participants were instructed on how to properly wear and use the PSM. According to the manufacturer's guidelines, the BH-BT skin electrodes were moistened and the chest belt was worn around the trunk just below the chest muscles. Second, participants wore personal protective equipment (i.e. gloves, toe guards, kneepads, hard hat, and safety glasses) selected according to the safety job analysis carried out to control and minimize any potential risk and to increase the realism of the construction task. Third, a material handling technique based on the US National Institute for Occupational Safety and Health guidelines was explained to reduce the risk of back injury. Three videos published by private health and safety education organizations were also shown to demonstrate how to handle heavy materials properly. Fourth, the working schedule and conditions were explained, and the assembling procedure was presented and demonstrated. Finally, participants performed a stretching procedure to further decrease the risk of musculoskeletal injuries. Moreover, a trained lab assistant assisted the participants at the beginning of the experiments to minimize the learning curve and to prevent errors in carrying out the assembling procedure.

Analysis of the physical strain productivity relationship

Assuming that physical strain and productivity are related, it is possible to express the relationship as:

$$\text{Productivity} = f(\text{PhysicalStrain})$$

Productivity assessment

Among the proposed productivity definitions, the inverse of the task level–single factor productivity definition proposed by the Construction Industry Institute (1990) is considered:

$$\begin{aligned}&\text{Productivity (units of work per work} - \text{hour)}\\&\quad = \text{quantity installed/work} - \text{hours expended}\end{aligned}$$

Applying the definition of the designed task, productivity was defined as:

$$\begin{aligned}&\text{Productivity (panels / min)}\\&\quad = \text{unit of completed work / labour period}\end{aligned}$$

The unit of completed work was one row of three panels and four supports and the labour period was the time (in minutes) necessary to accomplish the unit of completed work. Moreover, the time spent by participants in performing actions not related to the simulated task (e.g. checking BH-BT, and fastening the toe guards) was not calculated as labour period.

A video camera continuously recorded the experiments. Therefore, the assessment of the labour period for each unit of completed work was obtained by analysing the video recordings and the associated time stamps.

Physical strain assessment

HR monitoring has been proved to be an effective method in assessing physical strain in field situations. Therefore, it was assumed that

$$\text{Productivity} = f(\text{PhysicalStrain}) = f(\text{HR})$$

However, various factors other than physical activity can influence HR. Therefore, the following factors were considered to effectively implement HR as a physical strain index.

Environmental conditions. Temperature and humidity can influence HR and physical strain regardless of the workload. Thus, environmental conditions were maintained stable during the experiments. In particular, wet bulb globe temperature (WBGT) was adopted as the environmental condition index and it was monitored by the environmental station WBGT Heat Stress Meter (Sper Scientific, Scottsdale, AZ, USA).

Emotional/mental activity. Mental stress tends to increase HR. Thus, the designed working conditions (e.g. participants were told to take as many pauses as they needed) and introductory training session at the lab (e.g. the assembling procedure was clearly shown and a lab assistant aided the participants at the beginning of the experiments) aimed to minimize participants' mental workload while performing the construction activity for the first time.

Hydration. To ensure proper hydration, water was provided. As part of the initial training, participants were instructed to drink as much water as they needed.

Absolute and RHR assessment. To take into consideration individual characteristics in assessing physical strain, RHR was calculated according to Equation 1:

$$\text{RHR}[\%] = (\text{HR} - \text{HRrest})/(\text{HRmax} - \text{HRrest}) \times 100$$

HRmax can be accurately estimated using a cardiac stress test. However, stress tests may be dangerous for unfit individuals. In fact, numerous HRmax prediction equations were proposed to estimate HRmax without performing cardiac stress tests (Robergs and Landwehr, 2002). Therefore, HRmax was estimated as a function of participant age according to the following equation (Tanaka *et al.*, 2001):

$$\text{HRmax} = 208 - 0.7 \times \text{Age}$$

HRrest was calculated according to the procedure adopted by Kirk and Sullman (2001). After wearing and activating the PSM, participants were asked to sit and rest for at least 15 minutes and HRrest was obtained as arithmetic mean of the HR measured in the last 10-minute period.

Therefore, two types of physical strain–productivity relationship were considered:

$$\text{Productivity} = f(\text{PhysicalStrain}) = f(\text{HR})$$

$$\text{Productivity} = f(\text{PhysicalStrain}) = f(\text{RHR})$$

Illnesses, medical devices, and medication. Participants completed a health history questionnaire during the screening phase to exclude participants with cardiovascular diseases and/or those that were taking prescribed medications able to affect HR monitoring effectiveness in determining physical strain. Furthermore, the designed experimental guidelines allowed identifying and, if necessary, excluding participants taking any type of over-the-counter medication.

Digestion, and stimulants and depressive substances. Participants were instructed not to drink stimulants or depressive substances or eat within two hours prior to the experiment. At the beginning of each experiment, they were also informally questioned on this topic. Moreover, the food provided during the experiments was light and easy to digest, and food intake was recorded to test any influence of digestion on HR.

Given the close relation between the circulatory and respiratory systems (Oglesby *et al.*, 1989; Alberts *et al.*, 2004), it was also assumed that breathing rate (BR) monitoring could be coupled with HR monitoring and give a better estimate of physical strain. As for HR, also BR measurements should be expressed in relation to individual maximal and resting BR to take into consideration individual characteristics. However, the stress tests necessary to assess the maximal BR may be dangerous for unfit individuals (Abdelhamid, 1999). Further, in the literature there is no reliable formula based on individual characteristics (e.g. age, gender) capable of estimating the maximal breathing rate. Thus, it was not possible to determine the relative BR. Furthermore, it is not possible to directly convert BR to energy expenditure. Thus, only absolute BR was added to the previously selected independent variables.

$$\text{Productivity} = f(\text{PhysicalStrain}) = f(\text{HR}, \text{BR})$$

$$\text{Productivity} = f(\text{PhysicalStrain}) = f(\text{RHR}, \text{BR})$$

Participants' physiological parameters (i.e. HR and BR) were continuously monitored by BH-BT.

Collected data

A participant identification code (PIC) was adopted to clearly distinguish between participants and show their gender and working schedule. The PIC structure is composed of three elements divided by a dot: a different capital letter for each experimental session; subject gender (i.e. M for male and F for female); and number of performed working periods (i.e. 4 or 2).

Participants accomplished the experiments with no adverse events (i.e. no participant suffered any harm or unintended effect). The HR data of participant J. F.4 could not be saved due to a physiological monitoring software crash. Hence, she was excluded from any analysis. A summary of the collected data is provided in the following tables: Table 3 presents WBGT (°C) summary statistics; Table 4 shows participants' physical characteristics (i.e. height, weight, HRrest, and HRmax); and, Tables 5–8. present productivity (panels/min), HR (beats per minute, bpm), RHR (%), and BR (breaths per minute, bpm) summary statistics.

Regression analysis

Regression analysis was applied to investigate the nature of the relationship between physical strain and task level productivity (P). As previously stated, two regression models were considered:

$$\text{P} = f(\text{HR}, \text{BR}) \text{ and } \text{P} = f(\text{RHR}, \text{BR})$$

The procedure to investigate the regression models consisted of: signal processing; regression line selection; analysis of outliers; and analysis of dependent variables' significance.

Signal processing

For each of HR, RHR, and BR the reporting interval was one second. However, the selected physiological parameters are mostly meaningless in assessing physical strain if measured in such short periods. To be meaningful, the data must be averaged in time periods in order of magnitude of minutes. Research studies that can be referenced to determine an effective time interval are not available. Thus, the independent and dependent variables were averaged in eight time intervals from 5 to 40 minutes (i.e. 5, 10, 15, 20, 25, 30, 35, and 40 minutes) to identify the meaningful time periods during the analysis.

Regression line selection

To characterize the nature of the relationship (e.g. linear, parabolic, logarithmic) between the dependent and the independent variables, a visual and statistical analysis of the scatter plots P vs. HR, P vs. RHR, and P vs. BR was performed for every time interval, and for each individual worker and for the group as a whole. This analysis did not identify any relationship at the individual worker level as shown in Figures 9–11. where each worker's data are on an independent cloud. At the group level, the analysis produced interesting results. As shown in Figure 3 to Figure 8 (Figure 3 to Figure 5 show the scatter plots for the time interval equal to 15 minutes, and Figure 6 to Figure 8 the scatter plots for the time interval equal to 40 minutes), the regression lines that fitted the group-level data best were parabolic for P-HR and P-RHR, and linear for P-BR.

Analysis of outliers

Before analysing the significance of the proposed group-level relationship, it was necessary to determine whether the data of one or more participants significantly deviated from the other data. Observing the scatter plots (e.g. Figure 9 to Figure 11), participant D.F.4's data points considerably diverged from the

Table 3 Wet bulb globe temperature (°C) summary statistics

PIC	A.M.4	B.M.4	C.M.4	D.F.4	E.F.4	F.F.4	G.M.2	H.M.2	I.M.2
Average	17.4	16.8	15.1	14.9	14.3	12.4	14.8	14.4	12.6
Minimum	16.7	16.3	13.9	14.7	13.9	11.5	14.2	13.6	11.1
1st quartile	17.3	16.3	14.9	14.8	14.1	12.3	14.6	14.1	12.3
Median	17.6	16.8	15.2	14.9	14.3	12.5	14.8	14.5	12.8
3rd quartile	17.6	17.1	15.4	14.9	14.4	12.6	15.0	14.7	13.1
Maximum	17.7	17.5	15.7	15.1	14.9	12.8	15.3	15.1	13.4

Table 4 Participants' physical characteristics

PIC	Height (m)	Weight (kg)	HRrest (bpm)	HRmax (bpm)
A.M.4[a]	1.78	71.8	64.2[b]	194.7
B.M.4	1.78	77.3	80.0	194.7
C.M.4	1.73	62.7	70.3	194.7
D.F.4	1.70	70.5	91.9	192.6
E.F.4	1.62	63.2	76.8	193.3
F.F.4	1.70	60.0	62.1	193.3
G.M.2	1.75	74.1	70.6	191.9
H.M.2	1.75	65.0	78.8	191.9
I.M.2[a]	1.78	72.0	57.7[b]	194.7
J.F.4	1.52	55	N.A.	N.A.

Notes: [a]Participants A.M.4 and I.M.2 are the same person.
[b]Since the subject accomplished both experimental sessions at the same time ($\approx 4 \div 9$ pm), the difference in HRrest may be due to the different WBGT during the experimental sessions (average WBGT 17.7°C for A.M.4 and 12.6°C for I.M.2).

Table 5 Productivity (panels/min) summary statistics

PIC	A.M.4	B.M.4	C.M.4	D.F.4	E.F.4	F.F.4	G.M.2	H.M.2	I.M.2
Average	1.76	1.34	1.98	1.24	1.73	1.36	1.16	1.73	1.86
Minimum	1.42	0.78	1.24	0.59	1.13	0.86	0.52	1.04	1.28
1st quartile	1.62	1.09	1.80	0.88	1.51	1.16	0.99	1.49	1.70
Median	1.73	1.35	1.94	1.35	1.70	1.38	1.13	1.80	1.82
3rd quartile	1.89	1.55	2.25	1.49	1.91	1.58	1.31	1.94	2.02
Maximum	2.77	2.43	2.77	1.88	3.00	2.17	2.09	2.43	2.50
Range	1.35	1.65	1.53	1.28	1.87	1.31	1.58	1.39	1.22

Table 6 Heart rate (bpm) summary statistics

PIC	A.M.4	B.M.4	C.M.4	D.F.4	E.F.4	F.F.4	G.M.2	H.M.2	I.M.2
Average	93.0	125.4	141.2	144.8	137.8	107.0	111.0	108.9	92.2
Minimum	71	82	86	87	88	68	78	0	53
1st quartile	89	121	137	136	132	101	107	106	88
Median	93	126	142	147	139	107	111	109	92
3rd quartile	97	130	149	155	146	113	115	112	96
Maximum	108	146	163	173	165	139	140	127	115
Range	37	64	77	86	77	71	62	127	62

Table 7 Relative heart rate (%) summary statistics

PIC	A.M.4	B.M.4	C.M.4	D.F.4	E.F.4	F.F.4	G.M.2	H.M.2	I.M.2
Average	22.0	39.5	57.0	52.5	52.4	34.3	33.3	26.7	25.2
Minimum	5.2	1.7	12.6	–4.9	9.6	4.5	6.1	–0.7	–3.5
1st quartile	19.0	35.7	53.6	43.8	47.4	29.6	30.0	24.1	22.1
Median	22.1	40.1	57.6	54.7	53.4	34.2	33.3	26.7	25.0
3rd quartile	25.1	43.6	63.3	62.7	59.4	38.8	36.6	29.6	27.9
Maximum	33.6	57.5	74.5	80.5	75.7	58.6	57.2	42.6	41.8
Range	28.4	55.8	61.9	85.4	66.1	54.1	51.1	43.3	45.3

Table 8 Breathing rate (bpm) summary statistics

PIC	A.M.4	B.M.4	C.M.4	D.F.4	E.F.4	F.F.4	G.M.2	H.M.2	I.M.2
Average	19.4	21.8	19.6	0.0	16.6	25.6	18.2	16.6	13.3
Minimum	12.5	14.8	11.7	12.9	9.6	16.6	11.6	11.3	8.6
1st quartile	16.9	18.8	16.6	20.8	15.0	24.1	16.0	15.0	11.6
Median	19.5	22.0	19.5	23.5	16.5	25.7	18.4	16.4	12.9
3rd quartile	21.8	24.4	22.5	25.5	18.1	27.5	20.2	18.2	14.7
Maximum	26.2	29.0	29.3	30.3	24.6	33.0	23.5	23.1	20.5
Range	13.8	14.2	17.6	17.4	15.0	16.4	11.8	11.7	11.9

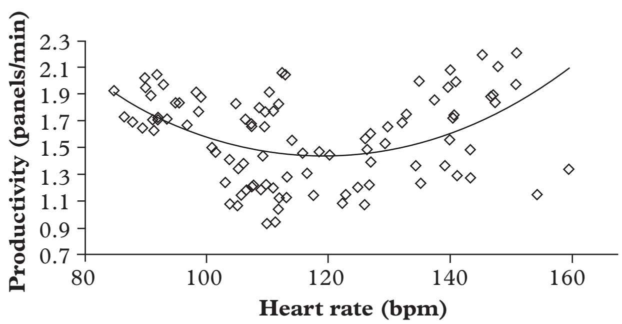

Figure 3 Scatter plot productivity vs. heart rate, time interval 15 min

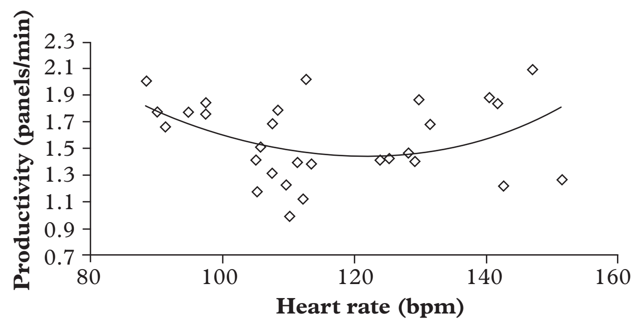

Figure 6 Scatter plot productivity vs. heart rate, time interval 40 min

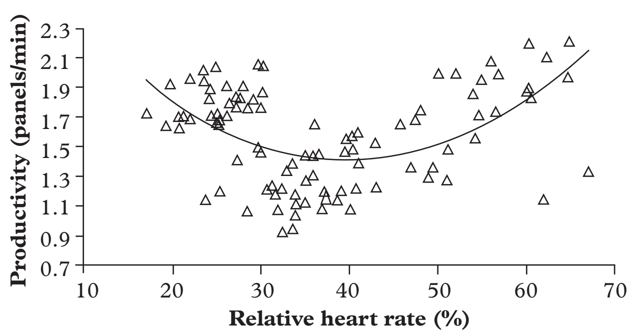

Figure 4 Scatter plot productivity vs. relative heart rate, time interval 15 min

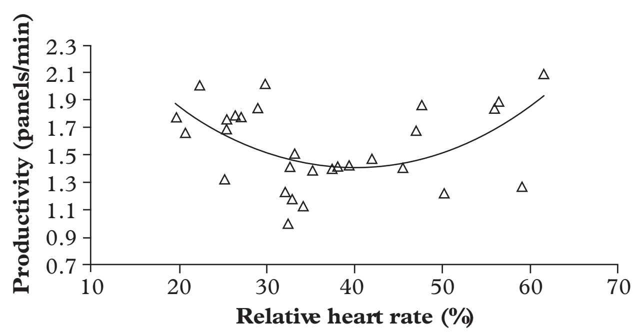

Figure 7 Scatter plot productivity vs. relative heart rate, time interval 40 min

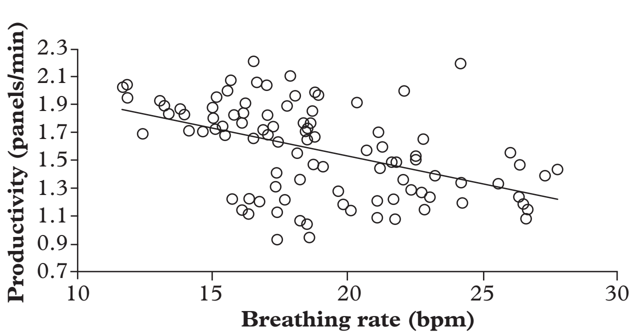

Figure 5 Scatter plot productivity vs. breathing rate, time interval 15 min

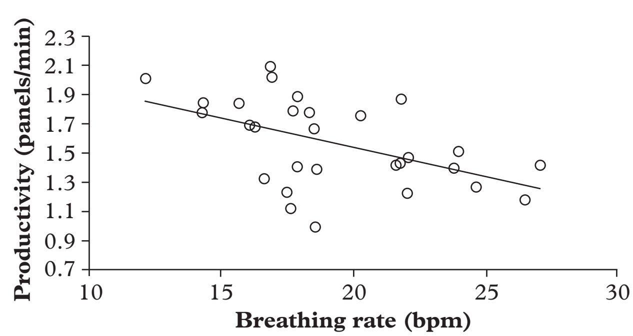

Figure 8 Scatter plot productivity vs. breathing rate, time interval 40 min

parabolic relationships P-HR and P-RHR, but not from the linear relationship P-BR. Further, the coefficient of determination (R^2) for P-HR and P-RHR considerably increases if participant D.F.4 is excluded (Figure 12 and Figure 13), while it slightly decreases for P-BR (Figure 14). In particular, R^2 growth for P-HR and P-RHR is of an order of magnitude greater than R^2 reduction for P-BR. In addition, participant D.F.4 was the only participant that showed an extremely high HRrest (Table 4) and that could not perform the entire experiment due to extreme fatigue. It was concluded that this participant had not stated the truth on the physical activity questionnaire and, therefore, she was not supposed to be included in the study. Thus, participant D.F.4's data were deemed outliers and excluded from the regression analysis.

Analysis of dependent variables' significance

Several regression models were generated and analysed to determine whether the independent variables were statistically significant at the group level (note: all the following descriptions of analyses and relative discussion refer to group-level relationships).

Regression model generation

First, five predictor configurations were established:

- $P = f\,(HR, HR^2)$;
- $P = f\,(RHR, RHR^2)$;
- $P = f\,(BR)$;
- $P = f\,(HR, HR^2, BR)$; and,
- $P = f\,(RHR, RHR^2, BR)$.

Then, four datasets were generated (Table 9) by increasing the dissimilarity among the selected data. For example, dataset A comprised data collected in the first 50 minutes of each WP for participants that followed the four WPs schedule, whereas dataset D

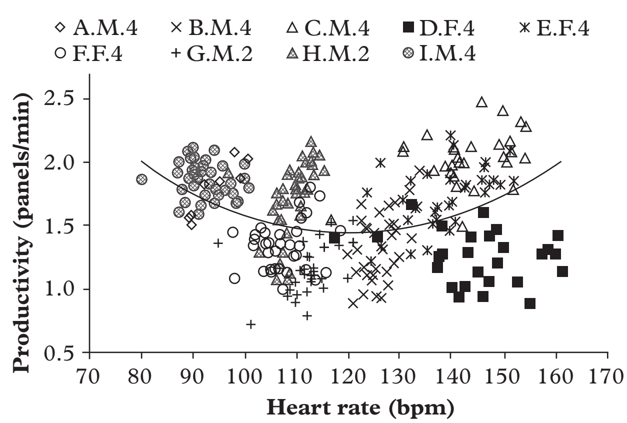

Figure 9 Scatter plot productivity vs. heart rate, time interval 5 min

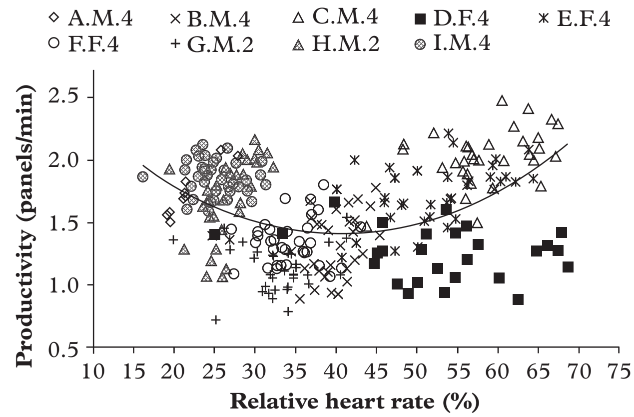

Figure 10 Scatter plot productivity vs. relative heart rate, time interval 5 min

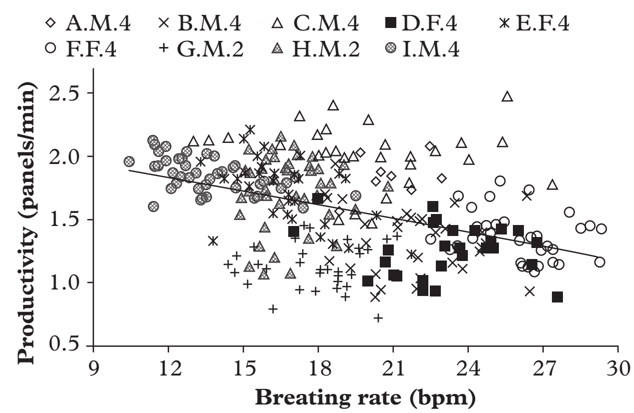

Figure 11 Scatter plot productivity vs. breathing rate, time interval 5 min

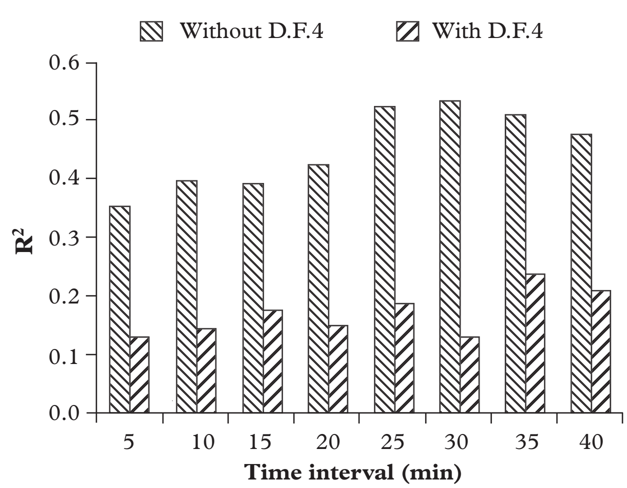

Figure 12 R^2 of productivity vs. heart rate for each time interval

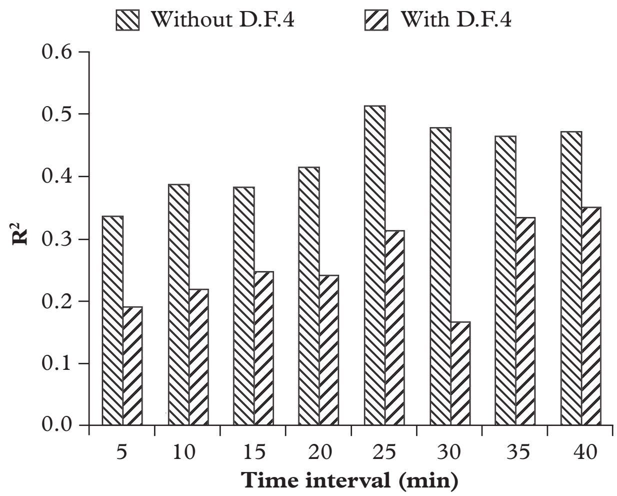

Figure 13 R^2 of productivity vs. relative heart rate for each time interval

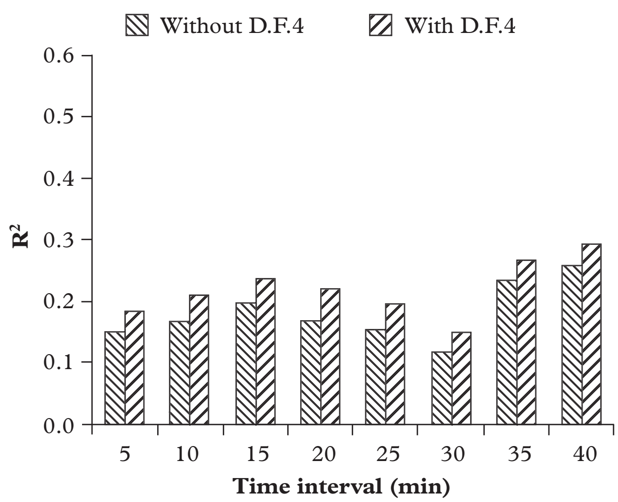

Figure 14 R^2 of productivity vs. breathing rate for each time interval

comprised all the collected data for all the participants. Therefore, dataset A was the most homogenous and dataset D was the most heterogeneous.

Hence, considering that the variables were averaged on eight time intervals, 160 regression models (i.e. 5 predictor configurations × 4 datasets × 8 time intervals = 160 regression models) were generated.

Regression model analysis

The statistical significance of the independent variables and the goodness of fit of the regression model were verified by (1) performing an F-test for the overall fit and t-tests for the individual variables; (2) verifying that the scatter plots of the residuals vs. each variable were similar to null plots; and (3) calculating R^2 and standard error of estimate (SEE) of each regression model.

R^2 and SEE are presented for each regression model in the following tables (Tables 10–13. ; the regression models that either failed one of the statistical tests or whose scatter plots did not resemble a null plot are shown in 'strikethrough' font).

Table 9 Dataset characteristics

Dataset	Schedule	Monitored WPs
A	S1	First 50 of each WP
B	S1 and S2	Schedule S1: first 50 of each WP Schedule S2: first 50 of WP1
C	S1 and S2	Schedule S1 and S2: first 50 of each WP
D	S1 and S2	All the collected data

Discussion

The analysis of the generated regression models allowed several important conclusions to be drawn at the group level that can be abstracted to a general population of workers with similar characteristics as the sample of subjects (i.e. young, untrained, and physically healthy).

First, it was concluded that BR is not a significant predictor. The performance of the regression models adopting BR as a unique independent variable was unacceptable (R^2 is greater than 0.5 only 3 times out 32). Furthermore, BR was not a statistically significant predictor in many of the other regression models adopting BR as an independent variable (i.e. P = f (HR, HR^2, BR) and P = f (RHR, RHR^2, BR)). Thus, the regression models comprising BR were excluded from further discussion.

Second, R^2 tended to increase (and SEE to decrease) from the smallest time interval (i.e. 5 minutes) reaching a plateau between 25 and 40 minutes regardless of the variables and datasets used. Moreover, the regression lines were very similar between 25 and 40 minutes regardless of the variables and datasets used (e.g. Figure 15 and Figure 16).

Third, regression models using RHR did not outperform the models using HR. Considering the time intervals between 25 and 40 minutes, differences in R^2 and SEE between P = f (HR, HR^2) and P = f (RHR, RHR^2) models were generally negligible. This result was unexpected because RHR should be a better predictor than HR when several participants are involved. The reason behind this outcome could be

Table 10 R^2/SEE for regression models based on dataset A

	Predictor configuration					
Time int. (min)	HR, HR^2	RHR, RHR^2	BR	HR, HR^2, BR	RHR, RHR^2, BR	Data points
5	0.467/0.248	0.480/0.245	0.240/0.296	0.499/0.242	0.519/0.237	169
10	0.554/0.208	0.566/0.205	0.293/0.260	0.587/0.201	0.609/0.196	81
15	0.585/0.202	0.603/0.197	0.322/0.255	~~0.608/0.198~~	~~0.632/0.192~~	51
20	0.611/0.177	0.633/0.171	0.335/0.227	~~0.632/0.175~~	~~0.663/0.167~~	35
25	0.791/0.131	0.807/0.126	0.608/0.176	~~0.813/0.126~~	~~0.834/0.119~~	28
30	0.750/0.142	0.754/0.141	0.535/0.187	~~0.767/0.142~~	~~0.778/0.138~~	18
35	0.783/0.126	0.785/0.126	0.583/0.169	~~0.795/0.128~~	~~0.806/0.124~~	17
40	0.719/0.139	0.736/0.135	0.488/0.181	~~0.727/0.143~~	~~0.753/0.136~~	16

Note: The regression models that either failed one of the statistical tests or whose scatter plots did not resemble a null plot are shown in 'strikethrough' font.

Table 11 R^2/SEE for regression models based on dataset B

	Predictor configuration					
Time int. (min)	HR, HR^2	RHR, RHR^2	BR	HR, HR^2, BR	RHR, RHR^2, BR	Data points
5	0.449/0.258	0.405/0.268	0.208/0.309	0.489/0.249	0.465/0.255	199
10	0.525/0.222	0.468/0.235	0.244/0.279	0.565/0.214	0.531/0.222	96
15	0.562/0.209	0.506/0.222	0.271/0.267	0.594/0.203	0.560/0.211	60
20	0.634/0.175	0.559/0.193	0.275/0.244	~~0.656/0.173~~	0.604/0.185	41
25	0.707/0.167	0.636/0.186	0.284/0.257	~~0.733/0.162~~	0.683/0.177	34
30	0.744/0.156	0.616/0.191	~~0.143/0.278~~	~~0.759/0.156~~	~~0.663/0.184~~	21
35	0.801/0.126	0.667/0.163	0.425/0.209	~~0.804/0.129~~	~~0.692/0.162~~	20
40	0.776/0.139	0.663/0.170	0.413/0.218	~~0.788/0.140~~	~~0.698/0.167~~	19

Note: The regression models that either failed one of the statistical tests or whose scatter plots did not resemble a null plot are shown in 'strikethrough' font.

Table 12 R^2/SEE for regression models based on dataset C

	Predictor configuration					
Time int. (min)	HR, HR^2	RHR, RHR^2	BR	HR, HR^2, BR	RHR, RHR^2, BR	Data points
5	0.413/0.261	0.373/0.270	0.182/0.308	0.463/0.250	0.440/0.256	229
10	0.479/0.228	0.430/0.239	0.215/0.279	0.534/0.217	0.504/0.224	111
15	0.509/0.220	0.468/0.229	0.243/0.272	0.559/0.211	0.534/0.216	69
20	0.553/0.193	0.496/0.205	0.243/0.248	0.595/0.186	0.558/0.194	47
25	0.674/0.169	0.620/0.182	0.384/0.229	0.714/0.160	0.673/0.171	40
30	0.660/0.171	0.565/0.194	0.322/0.236	~~0.681/0.170~~	~~0.601/0.190~~	24
35	0.636/0.177	0.680/0.166	0.306/0.238	~~0.682/0.170~~	~~0.728/0.157~~	23
40	0.642/0.164	0.558/0.182	0.314/0.221	~~0.670/0.161~~	~~0.606/0.176~~	22

Note: The regression models that either failed one of the statistical tests or whose scatter plots did not resemble a null plot are shown in 'strikethrough' font.

the procedure used to calculate RHR. RHR was obtained as function of HRmax, and HRmax was exclusively based on participants' age (HRmax = 208 – 0.7 Age). Although the formula used to assess HRmax is widely accepted and used in academia, it rarely succeeds in providing an accurate estimation of the real maximal HR. Thus, the inaccurate HRmax estimate might have negatively affected regression

Table 13 R^2/SEE for regression models based on dataset D

	Predictor configuration					
Time int. (min)	HR, HR^2	RHR, RHR^2	BR	HR, HR^2, BR	RHR, RHR^2, BR	Data points
5	0.347/0.285	0.332/0.288	0.150/0.324	~~0.398/0.274~~	0.393/0.275	296
10	0.394/0.259	0.382/0.262	0.165/0.303	0.444/0.249	0.439/0.250	143
15	0.389/0.261	0.380/0.262	0.195/0.297	0.449/0.249	0.444/0.250	90
20	0.422/0.243	0.412/0.245	0.168/0.289	0.466/0.235	0.458/0.237	63
25	0.530/0.223	0.512/0.227	0.256/0.278	~~0.567/0.217~~	~~0.547/0.222~~	48
30	0.525/0.218	0.491/0.226	0.234/0.272	~~0.557/0.214~~	~~0.523/0.222~~	32
35	0.584/0.207	0.623/0.197	~~0.172/0.287~~	~~0.606/0.205~~	~~0.643/0.195~~	31
40	0.455/0.225	0.436/0.229	~~0.208/0.266~~	~~0.493/0.222~~	~~0.472/0.227~~	27

Note: The regression models that either failed one of the statistical tests or whose scatter plots did not resemble a null plot are shown in 'strikethrough' font.

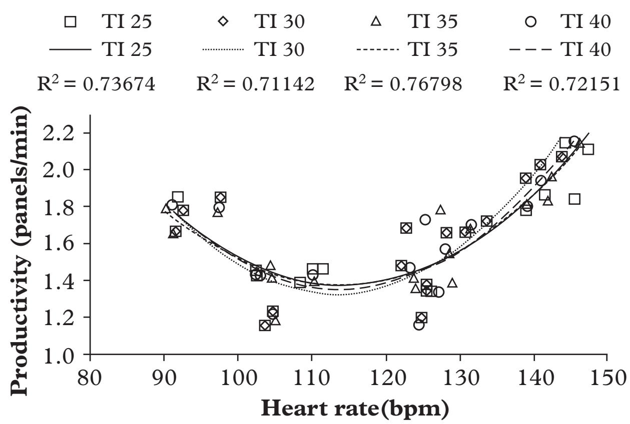

Figure 15 Data points and regression lines for dataset A, P = *f* (HR, HR^2), and time interval 25 ÷ 40 min

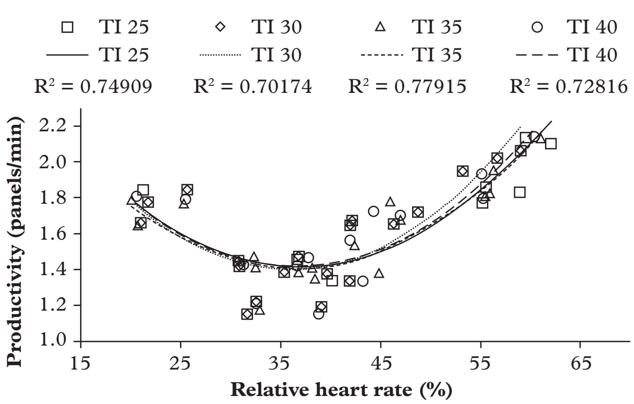

Figure 16 Data points and regression lines for dataset A, P = *f* (RHR, RHR^2), and time interval 25 ÷ 40 min

model performance. Therefore, since R^2 and SEE for P = f (HR, HR^2) and P = f (RHR, RHR^2) models were consistent and comparable in the great majority of the cases, it was not possible to clearly determine which independent variable guaranteed the best performance.

Fourth, considering time intervals between 25 and 40 minutes, regression model performance gradually worsened from dataset A to dataset D. In particular, regression model performance was optimal (i.e. $R^2 > 0.7$) for dataset A, satisfactory for datasets B and C (i.e. $R^2 \approx 0.6 \div 0.7$), and unsatisfactory for dataset D (i.e. $R^2 < 0.6$). These outcomes were expected. Datasets were created obtaining and increasing dissimilarity in the data (from dataset A to dataset D). Thus, it is reasonable that the more similar the data are the better performance the regression models show.

Conclusions and future research

The relationship between physical strain and task level productivity was investigated by applying regression analysis. HR, RHR, and BR were selected as predictors of physical strain and, therefore, of productivity. Thus, the task level productivity and physiological parameters of nine participants performing a four-hour simulated construction task were monitored. The collected data were used to generate 160 regression models. This investigation initially unsuccessfully attempted to establish a relationship between physiological parameters and productivity at the individual worker level. However, the analysis of the models' statistical significance and goodness of fit proved that a parabolic relationship between productivity and either HR or RHR can be established at the group level, whereas BR is not a significant predictor of productivity. The researchers explained the lack of relationship between productivity and either HR or RHR at the individual level as being probably due to the duration of a single experiment (i.e. half workday).

However, several limitations may affect the research study significance within the construction industry. First, participants accomplished only one task (i.e. assembling a raised deck). Hence, the obtained physical strain–task level productivity relationships may not be applicable to other construction activities. Second, the number of participants was limited and had similar physical features (i.e. participants were between 19 and 23 years old with comparable body mass index). Thus, the sample size may be too small to conclusively analyse the physical strain–task level productivity relationship (Heyward, 2006). Third, participants did not have any relevant construction experience and did not work as 'real' construction workers even though the construction task was designed according to the construction industry's standard of practice. In fact, participants worked only one day for four hours. Finally, participants performed within a controlled environment (e.g. temperature) and under monitored conditions (e.g. hydration, medications) without many of the construction workforce typical stressors.

Although the research outcomes are not conclusive in determining how physical strain affects task level productivity and, therefore, they are not sufficient to develop a management tool to improve task level productivity performance, they provide a step forward in the study of workforce physiological monitoring for task level productivity improvements. Therefore, the research outcomes contribute to the progression of knowledge about construction workforce physiological monitoring. The existing literature outlines theories generally based on anecdotal evidence and/or heuristic approaches and, therefore, these theories are rarely substantiated by the collection and analysis of physical strain and performance data. With this research, the physical strain–task level productivity relationship is, for the first time, analysed using actual physical strain and productivity data. Moreover, original topics for future research can be identified thanks to the research outcomes. First, the collected data show that most data points for each participant tend to group within HR/RHR bands of different dimension. Moreover, these bands are located in the upper right-hand side, upper left-hand side, or lower centre area of the parabolic curve (Figure 9 and Figure 10). Thus, experiments that analyse the performance of several participants working in the same HR/RHR bands are necessary to clearly understand whether it is possible to identify individual factors (e.g. gender, size, muscle mass, age) capable of predicting subjects' behaviour. Moreover, subjects working within a HR/RHR band positioned in the upper left-hand side (i.e. low HR/RHR) should be compared with subjects performing within a HR/RHR band positioned in the upper right-hand side of the parabolic curve (i.e. high HR/RHR). In fact, although these two groups experience different level of physical strain, they are capable of performing at similar productivity levels. Therefore, it would be interesting to analyse how experiencing different levels of physical strain may affect the subjects' capacity to perform work over time intervals longer than four hours. The collected data also suggested that participants departing from the parabolic curve on the lower right-hand side might undergo critical physical strain. Only one subject presented this behaviour and reached severe fatigue. Thus, experiments involving subjects dealing with severe physical strain are highly desirable in determining whether the parabolic curve can be used as a safe zone for preventing workers from undergoing extreme physical strain. Moreover, the methods, results, and recommendations for future research directions discussed in this article can not only promote improvements in workforce productivity, but also enhance wellbeing and safety, and quality of work. Examples of expected future applications are: optimization of workflow and work break schedule at individual and crew levels; reduction of exposure to excessive strain; optimization of personnel selection and worker–activity matching; and development of more effective training courses, procedures, rules, and regulations. Furthermore, the outcomes can benefit the workforce management of occupations other than construction workers, such as manufacturing workers or first responders.

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