This is the Pre-Published Version.
Building and Environment (Final Accepted Manuscript), Volume 58, December 2012, Pages 163-171

Determining an optimal recovery time for construction rebar workers after working to exhaustion in a hot and humid environment

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Abstract

This paper is an extension to a paper previously published in the journal *Building and Environment*. Having determined an optimal recovery time in a controlled climatic environment, this paper aims to investigate the real impact on construction rebar workers by replicating the clinical experimentation to a series of field studies. Field studies were conducted during the summer time in Hong Kong. Nineteen rebar workers performed tasks of fixing and bending steel reinforcement bars on two building construction sites until voluntary exhaustion and were allowed to recover on site until their physiological conditions returned to the pre-work level or lower. Physiological Strain Index (PSI) was used as a yardstick to determine the rate of recovery. A total of 411 sets of meteorological and physiological data collected over fourteen working days between July and August of 2011 were collated to derive the optimal recovery time. It was found that on average a rebar worker could achieve 94% recovery in 40 min; 93% in 35 min; 92% in 30 min; 88% in 25 min; 84% in 20 min; 78% in 15 min; 68% in 10 min; and 58% in 5 min. Curve estimation results showed that recovery time is a significant variable to predict the rate of recovery (R^2 = 0.99, P < 0.05). Additional rest times should be introduced between works in extreme hot weather to enable workers to recover from heat stress. Frequency and duration of each rest time should be agreed among different stakeholders based on the cumulative recovery curve.

Keywords: Heat stress; Physiological strain index (PSI); Heat tolerance time; Field studies; Rebar workers; Rest time

1. Introduction

Heat stress, having physiological effects on workers, can lead to reduction of work enthusiasm and productivity, increased accident rate [1], heat illness, and death [2-4]. Such extreme conditions are commonly encountered in many occupational settings such as steel and iron manufacturing, glass factories, mining, textiles, ceramics, food canneries, and outdoor operations [5]. Construction industry is a priority area for research and interventions because of its high number of work-related fatal and non-fatal injuries [6]. Employees engaged in the construction industry account for a small proportion, but have a higher risk of work-related illnesses and accidents than workers in other branches of industry and the public sector [7-8]. The construction industry is found to be more hazardous than most other sectors [9] because it involves highly demanding physical tasks with various types of stresses resulted from awkward posture, excessive force demands, highly repetitive actions and excessive energy expenditure [10]. Physically demanding works combined with the exposure to high temperature, humidity, solar radiation but poor air ventilation can further increase the physical stress of workers during the daylong operation [11]. Time integrated fatigue accompanied by heat incurred disorders may lead to different types of injuries and accidents [12]. Such fatigue stretched over a period of months and years may cause physical, physiological and musculoskeletal disorders in the long run [13].

In Hong Kong, the construction industry recorded the highest number of fatalities and accident rate among different major industry sectors [14]. The incidence of heat stress within the construction industry has been alarming and caused a number of verifiable reported deaths [2, 4]. The Hong Kong SAR Government and the construction industry have expressed concerns over working in hot weather and promulgated a series of fundamental practice notes and effective guidelines on working in hot weather [15-17]. In addition, the Hong Kong Observatory issues very hot weather warnings when Hong Kong is threatened by very hot weather, to alert the general public to the risk of heat stroke and sunburn due to very hot weather [18]. Preventive measures on work arrangement, work-break cycle, cool down facilities were advocated to protect site personnel working in hot weather. The purpose of work-rest scheduling is to balance productivity demands with safety concerns and the physical workload of the personnel [19]. A proper design of a work-rest schedule is an effective means in improving a worker's comfort, health, and productivity [20]. Zhao et al. established a heat tolerance time model to determine safe work time in hot and humid environment [21]. Earlier research work by Chan et al. [22] has computed the maximum duration (Heat Tolerance Time) that a rebar worker could work continuously without jeopardizing his health. Naturally workers should be allowed to take a rest before or when such a threshold is reached. However, how long the workers should be allowed to recover in hot weather after working to voluntary exhaustion remains to be a question yet to be answered.

Recovery can play a considerable role to the well-being of rebar workers as well as in their productivity [23]. Sufficient rest can prevent the accumulation of fatigue and a loss of productivity. A key consideration of a rest is its recovery value [24]. Many studies focus on the recovery value in term of the response of physiological parameters in extreme hot environment [23, 25-26]. Limited studies considered recovery value in perspective of the length of rest at heat exposure. Chan et al. [27] adopted the physiological strain index (PSI) as a yardstick to determine an optimal energetic recovery time after a participant has exercised to exhaustion in a controlled hot (30°C) and humid (75% relative humidity) environment. The purpose of this paper is to examine the real impact on rebar workers by replicating the clinical experimentation to a series of field studies.

2. Materials and methods

2.1 Participants

Nineteen apparently healthy and experienced rebar workers participated in this research study. Exclusion criteria included: flu in the week prior to participation, and history of diagnosed major health problems including diabetes, hypertension, cardiovascular disease, neurological problem and regular medication intake. The physical characteristics of the participants were as follows (mean ± SE): age 45.0 ± 8.3 years old; height 169.2 ± 5.6 cm; body weight before work 65.0 ± 7.2 kg; body weight after work 64.0 ± 7.2 kg; percentage of body fat 16.5 ± 6.4%; resting heart rate 78.3 ± 8.5 beats per minute; resting diastolic blood pressure 82.0 ± 10.5 mmHg; resting systolic blood pressure 117.3 ± 9.4 mmHg. Participants were clearly informed of the purposes and the procedures of the study before starting any tests. Written consent was obtained from all participants prior to the study. Their participation was on a voluntary basis and participants could withdraw at any time without penalty. Data collected from the study was password-protected and kept centrally in a stand-alone server and was used for this study only. The study was conducted according to the Declaration of Helsinki and the protocol was fully approved by the Research Committee of the authors' host institution.

2.2 Measurements

A series of physiological parameters such as energy expenditure, breath frequency, METs, minute ventilation, heart rate, oxygen consumption, and respiratory exchange ratio were monitored by a metabolic cart during experimentation. In order to evaluate the feeling of fatigue during exercise, ratings of perceived exertion (RPE) scale were used which has been considered as a practical and cost-effective approach to quantifying the psychological-physiological effects [28-31]. The scales use both verbal anchors and numbers that have been reported to possess both categorical and interval properties [32]. The Borg CR10 Scale (a 10-point single-item scale) was employed in this study, with anchors ranging from 1 "very very easy" to 10 "maximal exertion" [33].

In order to estimate the level of strain and to initiate appropriate actions at an early stage, Moran et al. [34] introduced a Physiological Strain Index (PSI), which is based on heart rate and core temperature records in humans, to describe heat strain in quantitative terms during continuous exercise [35]. PSI is therefore applied in this study to measure how rest breaks influence the recovery of the heat strain process. PSI has been shown to effectively differentiate the heat strain associated with different climatic conditions, hydration levels, types of clothing including protective clothing, different exercise intensities, gender and the effects of aging [36-38]. It is an algorithm combining data from the heart rate and core temperature, in which output is scaled from 0 to 10 where 0 represents "no strain" and 10 "very high physiological strain". The mathematical expression of PSI can be found in Eq. (1).

$$PSI = 5 * (T_{ri} - T_{r0}) / (39.5 - T_{r0}) + 5 * (HR_i - HR_o) / (180 - HR_0) \quad (1)$$

Where T_{ri} and HR_i are simultaneous measurements taken at any time whilst the participant is under the controlled heat exposure; and T_{r0} and HR_0 are the resting values in the chamber prior to the exercise, and 39.5 and 180 represent maximal core temperature and heart rate respectively.

2.3 Standard procedures

Field studies were conducted during the summer time in Hong Kong (from July to August of 2011). Different stages of a construction process from foundation works to core superstructure structural works were studied to capture a wide spectrum of empirical data. Locations where the participants worked were recorded to ascertain the effects of heat stress under shade or direct sunlight. The study protocol is illustrated in Fig.1.

Prior to the study, participants were asked to rest at room temperature of approximately 23°C for 20 minutes to stabilize their body temperature and heart rates. During this period, the testing procedures were explained to each participant. Whilst taking the rest, participants were requested to complete a pre-study data collection sheet which includes questions on age, height, smoking habit, alcohol drinking habit, sleeping hours and other personal information. Smoking and alcohol drinking habits were recorded in 6 categories according to the amount of their alcohol intake and cigarette consumption [39-40].

Before the commencement of rebar work, heart rate (Heart rate monitor, Polar, Finland), blood pressure (HEM-712C, OMRON, Japan), and percentage of body fat (InBody 230, Biospace Co., Ltd., USA) of the participants were measured. The physiological parameters of the participants were measured by the portable metabolic cart (K4b2, COSMED, Rome, Italy). The weight of the metabolic cart is 1.5 kg including the battery and a specially designed harness. Wearing the portable gas analyzer during the work does not significantly alter the participants' energy demands [41]. In addition, a heat stress monitor (QUESTemp° 36, Australia) was deployed to measure the prevailing environmental data such as the dry bulb temperature, wet bulb temperature, globe temperature, relative humidity, and air velocity (wind speed) through an additional detachable air-probe.

When the participants arrived at their working place, they were asked to rest in seated posture for another 20 minutes to calm down and acclimatize themselves to the hot and humid environment. Four sets of PSI were measured (at 5 minute interval) in these 20 minutes. The minimum PSI (PSI min) was taken as a yardstick for comparison after the participants had worked to exhaustion to determine the necessary recovery time. During the work, participants performed steel bar bending and fixing tasks as per their usual daily work routine. They were permitted to drink water when they desired. The volume of water drunk was recorded. A train of objective physiological parameters were continuously monitored and recorded every 5 seconds during the test via a telemetry system ($K4b^2$, COSMED, Rome, Italy). Without disturbing participants' normal operation, participants were asked to report on a RPE value and their ear temperatures were measured every 5 minutes, to monitor the amount of strain or level of exhaustion from both subjective and objective perspectives. Ear temperature was routinely used to estimate core temperature. The ear-based measurement was obtained by using the infrared tympanic electronic thermometer (Genius TM ^{2}, COVIDIEN, USA), which was proved to be an accurate and precise way [42] and was used to measure body temperature in less than 2 seconds, hence disturbance to their normal duty was negligible [43]. The thermometer has a temperature range of 33.0 °C to 42.0 °C, with an accuracy of ± 0.1°C. Ear temperature was then adjusted to display the core temperature equivalent (Eq. (2)).

$$\text{Core Mode} = \text{Ear Mode} + 1.04\ °\text{C} \qquad (2)$$

Alongside with the measurement of physiological data, the heat stress monitor measures four environmental parameters simultaneously at 1 minute interval: ambient or dry bulb temperature, natural wet bulb temperature, globe temperature, relative humidity from which the corresponding WBGT index can be computed. In total 411 sets of meteorological and physiological data were collected from 19 rebar workers on two construction sites over fourteen working days between July and August of 2011 in Hong Kong. Fig.2 exhibits the frequency distribution of WBGT (N = 411).

Voluntary exhaustion is defined as a state of self-awareness when one starts to feel a general inability to physically continue to perform at the desired level due to all energy stores having been consumed [44]. It was measured by Rating of Perceived Exertion (RPE-10 point scale) in the current study. Voluntary exhaustion was reached when the participants reported a RPE of 10 or stopped working voluntarily, whatever come first, indicated that they could not continue working anymore. The time when the participants stopped working was recorded and was taken as the participants' heat tolerance time. The participants were then allowed to recover on site until their physiological conditions fully recovered. Full recovery was reached when the post-work PSI returned to the minimum level or lower, and the corresponding duration was defined as the recovery time. Blood pressure, heart rate and body weight were measured at the end of the recovery.

2.4 Statistical analysis

A descriptive statistical analysis on the physiological variables was conducted, followed by t-test and one-way analysis of variance (ANOVA). Extrapolation method was applied to estimate the rate of recovery beyond the upper range of the observed data [45] since it has been widely used for estimating physiological parameters [46-49]. Rate of recovery is defined as the percentage of recovery with respect to participant's PSI_{min} and is expressed mathematically as

Eq. (3).

$$\text{Rate of recovery} = PSI_{min} / PSI_{i} \quad (3)$$

where PSI_i are 5-minute interval measurements taken whilst the participant rested for recovery on site; and PSI_{min} is the minimum value whilst the participant rested on site prior to work.

Curve estimation was employed to determine the relationship between recovery time and rate of recovery. Linear, quadratic, cubic and compound estimation were conducted to find the most suitable model of recovery rate. All statistical analyses were performed at a level of 95% statistical significance ($p < 0.05$). These analyses were performed using the statistical software program SPSS 17.0.

3. Results

The statistical results (Mean ± Standard Deviation) of the percentage of body fat, resting heart rate, resting blood pressure, RPE before and after test are presented in Table 1. In this experiment, heat tolerance time is 73.7 ± 11.8 min (range 60 -110 min), and recovery time is 22.1 ± 4.8 min (range 15-35 min).

3.1 Objective physiological indices

It can be seen in Fig.3 that core temperature of the participants increased when they exposure to hot and humid environment. In the first 35-min exercise period, core temperature increased rapidly, and the increment of the core temperature is large. After the first 35 min, core temperature of most participants started to decrease and then maintained at a relative stable condition. It should be noted that core temperature close to 38.4°C may reach heat tolerance limit and possibly result in collapse. The trend of heart rate change of 19 participants is similar (Fig.4). Significant differences in core temperature at exhaustion ($p < 0.05$) were found between different fitness groups (Table 2). The average core temperature at exhaustion for workers with lower PBF (8%-14%) was 0.3°C higher than that of workers with higher PBF (15%- 27%) (Table 2).

During the rest time, the heart rate decreased slightly during the first 5 min and then maintained stably. During the period of rebar work, the heart rate increased gradually. The mean heart rate of the participants increased by 40 beats /min. Exhaustion is accompanied by a rapid heart rate. It should be noted that heat exposure limits and heat disorders may appear when heart rate soared or the heart rate overtake 138 bpm [50]. Average heart rate was 12 bpm lower for participants without alcohol intake in comparison to the occasional alcohol drinking participants, and 19 bpm lower than the average heart rate for usual alcohol drinking participants. As for the recovery time, heart rate dropped by 17, 25, and 27 bpm for non alcohol drinking, occasional alcohol drinking and usual alcohol drinking participants respectively (Table 3). Fig.5 shows that oxygen consumption of participants increased from

2-6 ml/min/kg at rest condition to 5-17 ml/min/kg while work. After the bending and fixing work, oxygen consumption decreased sharply during the first 5 min recovery time and then decreased slowly until approaching the baseline. Respiratory exchange ratio (RER) fluctuates between 0.9 and 1.3 during exercise and fluctuates between 0.6 and 0.9 during rest (Fig.6).

3.2 Ratings of Perceived Exertion (RPE)

Heat strain upon entering the hot and humid environment was 1.9 ± 0.7 which corresponds to “Easy”. It continued to increase ($p<0.05$) at each 5 min interval reaching 6.8 ± 0.9 which corresponds to “Very hard”. (Fig.7)

3.3 Recovery time

Table 4 shows the pre-work PSI and post-work PSI of the 19 participants. The minimum PSI of participants rest on site is identified as a baseline physiological strain. Table 5 shows the summary of recovery rate for the 19 participants. It can be seen that 42% of the participants achieved 100% recovery within the first 35 minutes. Table 6 shows the summary of extrapolated recovery rate and highlights the average rate of recovery at the corresponding time. Average PSI values at 5-minute intervals are calculated to construct a model for the rate of recovery. Fig. 8 illustrates the relationship of the rate of recovery and the corresponding recovery time. It is noted that R-square is a statistical measure of how well a regression line/curve approximates real data points [51]. Since R-square of cubic model reaches the highest value of 0.997, cubic curve is adopted as the best curve-fitting model and is expressed as Eq. (4).

$$R = 0.001T^3 - 0.069T^2 + 3.174T + 43.764 \qquad (4)$$

where R is rate of recovery (%); T is recovery time (min).

Finally a cumulative curve for determining an optimal recovery time for a rebar worker performing tasks in hot weather (WBGT = 30.81 ± 2.07°C) to exhaustion is constructed as shown in Fig.8. It can be seen that on average a rebar worker could achieve 94% recovery in 40 min; 93% in 35 min; 92% in 30 min; 88% in 25 min; 84% in 20 min; 78% in 15 min; 68% in 10 min; and 58% in 5 min.

4. Discussions

Core temperature may increase when one carries out physically demanding work under a hot and humid environment [52]. On the contrary, core temperature may decrease due to the sweating effect which brings down the body temperature to a tolerable level [53]. Metabolic heat production and the heat environment provoke aggravate physiological strain to exhaustion [53]. The current findings of core temperature at exhaustion at 38.4 ± 0.3 °C (range 38.2–38.7 °C) reinforce the results of previous studies which documented that heat exhaustion is associated with the attainment of a critically high core temperature approaching 38.5 °C

[54-56]. The great influence of aerobic fitness on heat tolerance time is mediated through the core temperature tolerated at exhaustion. A significant difference of 0.3°C between participants with different fitness levels in this study echoes the findings of previous studies for exercising in heat stress [57].

Heart rate is a general indicator of stress on the body [52]. Heart rate is the safest index because it is the earliest response of physiological strain [58]. Earlier research reported that the normal heart rates for performing heavy work in a hot and humid environment were in the range of 120-160 beat/min [50, 52]. Our findings of heart rate limits are in agreement with these studies. The effects of alcohol on heart rate have been examined by many researchers [59-60]. Our study also demonstrated that alcohol-drinking habit results in accelerated heart rate when working at a hot and humid environment. This finding provides convincing evidence to limit alcohol consumption when working in hot weather. It is recommended that construction workers should not consume any alcoholic drink during lunch time as it will lead to dehydration and make the workers prone to heat stress.

Observed increase in oxygen consumption is primarily due to prolonged heat exposure time and high work intensities. Respiratory exchange ratio (RER) is an index of effort adequacy [61]. RER is about 0.7 at rest in room temperature and is approximately 0.9 at rest on construction site. This value; however, can exceed 1 during intense exercise as CO_2 production by the working muscles becomes greater and more of the inhaled O_2 gets used rather than being expelled [62]. RER between 1.10 and 1.20 is considered to be a good descriptor of maximal effort in healthy subjects because an RER increment higher than the value of 1 is related to anaerobic metabolism activation [61].

Clinical experimental studies (with university students) [27] and field studies (with rebar workers) were conducted to monitor the physiological response and determine the optimal recovery time in hot and humid environment. Both studies provide a reliable safety limit to minimize the incidence of exhaustion during exercise/work-heat strain. The current findings reveal that participants reached exhaustion at a core temperature of 38.4 ± 0.3 °C (range 38.2–38.7 °C) is similar to those of 38.3 ± 0.3 °C (range 38.1–39.0 °C) measured in clinical experimental studies [27]. Our findings reveal that heart rate limit of rebar workers (138 ± 4.9 beat /min) is significantly higher than those of the participants when measured in clinical experimental studies (126 ± 3.6 beat /min) [27]. Humans adapt to environmental stressors through complex interactions between physiological and psychological factors [63]. Differences in individual characteristics affect an individual's ability to heat stress [64-65]. A high level of aerobic fitness or physiological treatments, such as aerobic training and heat acclimation, may be less effective in decreasing physiological strain or prolonging tolerance during exercise-heat stress [65].

Comparison of recovery rate between clinical experiment and field studies is illustrated in Table 7. A statistical technique comparing the population means of two samples indicate that they are correlated [66], however, paired sample t-test further illustrates that there is a significant difference of recovery rate between clinical experiment and field studies. The results show there is a strong positive correlation of 0.95, $P < 0.001$ (Table 8) and a significant difference at $t = 4.105$, $P < 0.005$ (Table 9) between the clinical study and the field study. The trend of energetic recovery for rebar workers and university students after working to exhaustion in a hot and humid environment is similar. However, rebar workers recovered considerably faster than university students in a hot and humid environment. Previous study suggests that there are many individual differences in the speed of physiological recovery [67]. Many studies suggest age, obesity, medication, and anxiety may negatively affect recovery [68-70]. Acknowledging that the sample size is limited in the current study, further research work should be done to increase the sample size and to identify the fundamental factors impacting on one's recovery ability.

An optimal recovery time can be determined based on the cumulative curve as shown in Fig.9, depending on how much percentage of recovery that the rebar workers intend to achieve, and how long the recovery time that can be afforded to the rebar workers. Measurement of the subjective feeling of fatigue by methods adopted in this study was used to evaluate the level of discomfort felt in the physical activity. The RPE of participants remained relatively constant at rest. As the high work intensities and prolonged heat exposure time, the RPE of participants increased at different pace because of their different physique.

5. Conclusions and recommendations

This study has demonstrated how to determine an optimal recovery time for construction rebar workers through monitoring physiological parameters. Physiological strain index (PSI) was used as a yardstick or an indicator to determine the rate of recovery. Nineteen rebar workers were asked to perform steel reinforcement bar bending and fixing tasks until exhaustion and to recover until their PSI returned to the minimum level at start. The average PSI values at 5-minute intervals were calculated to construct a curve for the rate of recovery. The energetic recovery trend of subjects after exhaustion in hot and humid environment is rapidly slowing curve. Earlier research [22] indicated that a 45-year old rebar worker who smokes and consumes alcohol occasionally and works at moderate work load intensity and at WBGT of 30°C and API of 30 will reach exhaustion in 72 minutes. To protect the health and safety of the worker, adequate rest time should be given to enable the worker to recover from the stressed physiological condition. The current study has contributed in providing an objective and scientific mechanism to determine an optimal recovery time.

The research team concurs with the recommendations of the prevailing guidelines and good practices [15-17] that contractors should: (a) take heed of weather reports; schedule regular breaks and rotate duties and worksites for workers; (b) provide shade/shelter and cooling device such as cooling fans with atomized water spray; (c) provide sufficient cool (10-15°C) drinking water at easily accessible drinking points. Meanwhile, workers should: (a) wear light-coloured, loose fitting, long-sleeved clothing and ventilated helmets; (b) avoid working under direct sunlight for prolonged periods of time and working in enclosed area with poor ventilation; (c) refrain from consuming alcoholic drinks or drinks containing caffeine during a working day and not take excessive alcoholic drinks prior to a working day as these will lead to dehydration and make them prone to heat stress.

It is recommended that (a) workers should not consume alcoholic and caffeinated drink on a working day; (b) supervisors and workers should be better educated to enhance their awareness of signs and symptoms of heat-related injuries, (c) Additional rest times should be introduced in extreme hot weather, frequency and duration of each rest time should be agreed among different stakeholders based on the cumulative recovery curve as defined in Figure 9; and (d) elderly workers (age > 60) should be refrained from working in extreme hot weather.

Construction management research, unlike other well defined and established disciplines, is very often being criticized of having an inappropriate research design and adopting an improper methodology. It is generally acknowledged that there is no best way of data collection [71]. This study has illustrated how experimentation can be designed and applied in construction management research. Although the current study is limited in sample size, further research work with enlarged sample size should be launched to verify the current findings.

The current study was conducted in normal work time (8:00 am-12:00 noon and 1:00 pm-6:00 pm). The likelihood of underestimating recovery time at sun peak hours or overestimating recovery time in the morning/evening has been noted and recognised as a potential limitation. Further studies to capture specific recovery time at certain times of the day and modeling work-rest schedules for construction workers working in hot weather are envisaged to be conducted.

In the light of the recovery model as well as the heat stress model [22], a set of good practices and indices, such as rest time and heat tolerance time, can be developed to ensure the health and safety of site personnel working in hot weather. Hence, it is recommended that further research on optimizing work-rest schedule for construction workers should be performed. This would be of tremendous value in better safeguarding workers' health and safety by reducing the occurrences of heat stress on site.

Workers engaged in different trade activities may have different degrees of susceptibility to heat stress. A trade by trade study would better reflect the real situation. Although this study applies specifically to the rebar trade, the same research methodology could be extended to other trades and to other countries in order to provide a holistic assessment of different trades of construction workers in future studies.

6. Acknowledgments

This project is funded by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (RGC Project No. PolyU510409). The research team is indebted to the technical support from technicians of the Hong Kong Polytechnic University and the Hong Kong Institute of Education. In particular, the participation of volunteers in this experimental study is gratefully acknowledged. This paper forms part of the research project titled "Experimental research on health and safety measures for working in hot weather", from which other deliverables will be produced with different objectives/scopes but sharing common background and methodology. The authors also wish to acknowledge the contributions of other team members including Prof Francis Wong, Prof Joanne Chung, Prof Esmond Mok, Dr Geoffrey Shea, Dr Min Wu, Dr Herbert Biggs, Dr Donald Dingsdag, and Miss Alice Guan.

7. References

[1] Hancher DE, Abd-Elkhalek HA. The effect of hot weather on construction labor productivity and costs. Cost Engineering 1998; 40(3): 32-6.

[2] Apple Daily. Worker died from heat stroke in golf course; 24 July 2007 (in Chinese).

[3] Apple Daily. 10% bar fixers have suffered from heat stroke; 5 July 2009(in Chinese).

[4] Apple Daily. Worker died from heat stroke in a falling accident; 19 Sep 2010 (in Chinese).

[5] Ka¨hko¨nen E, Swai D, Dyauli E, Monyo R. Estimation of heat stress in Tanzania by using ISO heat stress indices. Applied Ergonomics 1992; 23(2): 95-100.

[6] Hoonakkera P, Loushinea T, Carayona P, Kallmanc J, Andrew K, .Smith MJ. The effect of safety initiatives on safety performance: A longitudinal study. Applied Ergonomics 2005; 36(4): 461–9.

[7] Choudhry RM, Fang D. Why operatives engage in unsafe work behaviors: Investigating factors on construction sites. Safety Science 2008; 46: 566−84.

[8] Yia J, Kimb Y, Kimc K, Kood B. A suggested color scheme for reducing perception-related accidents on construction work sites. Accident Analysis & Prevention 2012; 48:185-92.

[9] Helander MG. Safety hazards and motivation for safe work in the construction industry. International Journal of Industrial Ergonomics 1991; 8 (3): 205-23.

[10] Maiti R. Workload assessment in building construction related activities in India. Applied Ergonomics 2008; 39(6) : 754-65.

[11] Tiwaria PS, Giteb LP. Evaluation of work-rest schedules during operation of a rotary power tiller. International Journal of Industrial Ergonomics 2006; 36(3): 203-10.

[12] Christensen EH, Sjøgaard K, Pilegaard M, Olsen HB. The importance of the work/rest pattern as a risk factor in repetitive monotonous work. International Journal of Industrial Ergonomics 2000; 25(4): 367–73.

[13] Waersted M, Westgaard RH. Working hours as a risk factor in the development of musculoskeletal complaints. Ergonomics 1991; 34(3): 265–76.

[14] Tam WY, Fung WH. Tower crane safety in the construction industry: A Hong Kong study. Safety Science 2011; 49:208-15.

[15] Construction Industry Council. Version 1. Guidelines on site safety measures for working in hot weather, vol. 2; June 2008.

[16] Department of Health, HKSAR Government. Preventive measures against heat stroke and sun burn. Available at: http://www.dh.gov.hk/english/press/2010/100706-3.html; 6 July 2010.

[17] Labour Department. Prevention of heat stroke at work in a hot environment. Available at: http://www.labour.gov.hk/eng/news/PreventionOfHeatStrokeAtWork.htm; 2008.

[18] Hong Kong Observatory, The Government of the Hong Kong Special Administrative Region. Cold and Very Hot Weather Warning. Available at http://www.hko.gov.hk/wservice/warning/coldhot.htm; 28 Dec 2011.
[19] Carnahan BJ, Redfern MS, Norman B. Designing safe job rotation schedules using optimization and heuristic search. Ergonomics 2000; 43(4): 543–60.
[20] Kopardekar P, Mital A. The effect of different work–rest schedules on fatigue and performance of a simulated directory assistance operator's task. Ergonomics 1994; 37 (10): 1697–1707.
[21] Zhao J, Zhu N, Lu SL. Productivity model in hot and humid environment based on heat tolerance time analysis. Building Environ 2009; 44(11): 2202-7.
[22] Chan PC, Yam CH, Chung W, Yi W. Developing a heat stress model for construction workers. Journal of Facilities Management 2012; 10 (1): 59-74.
[23] Maxwell NS, Castle PC, Spencer M. Effect of recovery intensity on peak power output and the development of heat strain during intermittent sprint exercise while under heat stress. Journal of Science and Medicine in Sport 2008; 11 (5): 491-9.
[24] Cakir A, Hart D, Stewart T. Visual Display Terminals. New York: Wiley; 1980.
[25] Leon LR. The thermoregulatory consequences of heat stroke: Are cytokines involved? Journal of Thermal Biology 2006; 31: 67–81.
[26] Mena H, Lumingu M, Dessureault P. Physiological responses to heat strain: A study on personal monitoring for young workers. Journal of Thermal Biology 2009; 34: 299–305.
[27] Chan APC, Wong FKW, Wong DP, Lam EWM, Yi W. Determining an optimal recovery time after exercising to exhaustion in a controlled climatic environment: Application to construction works. Building Environ 2012; 56: 28-37.
[28] Coquart JB, Legrand R, Robin S, Duhamel A, Matran R, Garcin M. Influence of successive bouts of fatiguing exercise on perceptual and physiological markers during an incremental exercise test. Psychophysiology 2009; 46(1): 209-16.
[29] Dunbar CC, Robertson RJ, Baun R, Blandin MF, Metz K, Burdett R, et al. The validity of regulating exercise intensity by ratings of perceived exertion. Med Sci Sports Exer 1992; 24(1):94-9.
[30] Foster C, Florhaug JA, Franklin J, Gottschall L, Hrovatin LA, Parker S, et al. A new approach to monitoring exercise training. J Strength Cond Res 2001; 15(1):109-15.
[31] Zeni AI, Hoffman MD, Clifford PS. Relationships among heart rate, lactate concentration and perceived effort for different types of rhythmic exercise in women. Arch Phys Med Rehabil 1996; 77(3):237-41.
[32] Borg G, Lindblad I. The determination of subjective intensities in verbal descriptions of symptoms. Reports from the Institute of Applied Psychology. Stockholm: Univ Stockholm; 1976. p. 75.
[33] Borg GA. Psychophysical scaling with applications in physical work and the perception of exertion. Scand J Work Environ Health 1990; 16(Suppl.):55-8.
[34] Moran DS, Montain SJ, Pandolf KB. Evaluation of different levels of hypohydration using a new physiological strain index. Am J Physiol 1998; 275(44): R854-60.
[35] Gotshall RW, Dahl DJ, Marcus NJ. Evaluation of a physiological strain index for use during intermittent exercise in the heat. J Exerc Physiol 2004; 3:22-9.

[36] Moran DS, Kenney WL, Pierzga JM, Pandolf KB. Aging and assessment of physiological strain during exercise-heat stress. Am J Physiol 2002; 282 [in revision].

[37] Moran DS, Shapiro Y, Laor A, Izraeli S, Pandolf KB. Can gender differences during exercise-heat stress be assessed by the physiological strain index? Am J Physiol 1999; 276(45):R1798-804.

[38] Moran DS, Shitzer A, Pandolf KB. A physiological strain index (PSI) to evaluate heat stress. In: Technical report T99-10. Natick, MA: US Army Research Institute of Environmental Medicine; 1999. p. 1-49.

[39] Frone MR. Work stress and alcohol use. Alcohol Res Health 1999; 23(4): 284-91.

[40] National Institute on Alcohol Abuse and Alcoholism. No. 32 PH 363. April 1996 Available at: http://pubs.niaaa.nih.gov/publications/aa32.htm.

[41] Flouris AD, Metsios, GS, Koutedakis Y. Enhancing the efficacy of the 20 m multistage shuttle run test. British Journal of Sports Medicine 2005; 39: 166–70.

[42] Lawson L, Bridges EJ, Ballou I, Eraker R, Greco S, Shively J, Sochulak V. Accuracy and precision of noninvasive temperature measurement in adult intensive care patients. Am J Crit Care 2007; 16(5): 485-96.

[43] Frakes MA, Duquette L. Body temperature preservation in patients transported by air medical helicopter. Air Med J 2008; 27(1): 37-9.

[44] World of Sports Science. Exhaustion. 2012. Available at: http://www.faqs.org/sports-science/Dr-Fo/Exhaustion.html

[45] Brezinski C, Zaglia RM. Extrapolation Methods. Theory and Practice. North-Holland: Amsterdam; 1991.

[46] Birkett WA, Edwards DF. The use of one-arm crank ergometry in the prediction of upper body aerobic capacity**.** Clinical Rehabilitation 1998; 12 (4): 319-27.

[47] Hirata A, Morita M, Shiozawa T. Temperature increase in the human head due to a dipole antenna at microwave frequencies. IEEE Transactions on Electromagnetic Compatibility 2003; 45 (1): 109-16.

[48] Macsween A. The reliability and validity of the Astrand nomogram and linear extrapolation for deriving VO2max from submaximal exercise data. Journal of Sports Medicine and Physical Fitness 2001; 41 (3): 312-7.

[49] Garcin M, Mille-Hamard L, Billat V. Influence of aerobic fitness level on measured and estimated perceived exertion during exhausting runs**.** International Journal of Sports Medicine 2004; 25 (4): 270-7.

[50] Tian Z, Zhu N, Zheng G, Wei H. Experimental study on physiological and psychological effects of heat acclimatization in extreme hot environments. Building Environ 2011; 46: 2033-41.

[51] Cuthbert D, Wood FS. Fitting equations to data: Computer analysis of multifactor data. 2nd edition. New York: Wiley-Interscience; 1999.

[52] Lu SL, Zhu N. Experimental research on physiological index at the heat tolerance limits in China. Building Environ 2007; 42(12):4016-21.

[53] Lumingu H, Dessureault P. Physiological responses to heat strain: a study on personal monitoring for young workers. J Thermal Biol 2009;34(6):299-305.

[54] Montain SJ, Sawka MN, Cadarette BS, Quigley MD, McKay JM. Physiological tolerance to uncompensable heat stress: effects of exercise intensity, protective clothing, and climate. J Appl Physiol 1994;77:216-22.

[55] Sawka MN, Young AJ, Latzka WA, Neufer PD, Quigley MD, Pandolf KB. Human tolerance to heat strain during exercise: influence of hydration. J Appl Physiol 1992;73:368-75.

[56] Cheung SS, McLellan TM. Heat acclimation, aerobic fitness, and hydration effects on tolerance during uncompensable heat stress. J Appl Physiol 1998; 84:1731-9.

[57] Selkrirk GA, McLellan TM. Influence of aerobic fitness and body fatness on tolerance to uncompensable heat stress. J Appl Physiol 2001;91:2055-63.

[58] Bernard TE, Kenney WL. Rationale for a personal monitor for heat strain. Am. Ind. Hyg. Assoc. J.1994; 55: 505-14.

[59] Kloner RA, Rezkalla SH. To drink or not to drink? That is the question. Circulation 2007;116: 1306-17.

[60] Spaak J, Tomlinson G, McGowan CL, Soleas GJ, Morris BL, Picton P, et al. Doserelated effects of red wine and alcohol on hemodynamics, sympathetic nerve activity, and arterial diameter. Am J Physiol Heart Circ Physiol 2008; 294: H605-12

[61] Mezzani A, Corrà U, Bosimini E, Giordano A, Giannuzzi P. Contribution of peak respiratory exchange ratio to peak VO2 prognostic reliability in patients with chronic heart failure and severely reduced exercise capacity. American Heart Journal 2003;145(6): 1102–7.

[62] Inglea L, Witteb K, Clelandc J, Clarkc A. The prognostic value of cardiopulmonary exercise testing with a peak respiratory exchange ratio of <1.0 in patients with chronic heart failure. Int J Cardiol 2008;127(1):88-92.

[63] Frisancho AR. Human adaptation: a functional interpretation. Ann Arbor: University of Michigan Press; 1981.

[64] Anderson GS. Human morphology and temperature regulation. Int. J. Biometeorol. 1999; 43: 99-109.

[65] Cheung SS, McLellan TM, Tenaglia S. The thermophysiology of uncompensable heat stress: physiological manipulations and individual characteristics. Sports Med. 2000; 29 (5): 329-59.

[66] Norusis MJ. SPSS 16.0 Statistical Procedures Companion. Second Edition. Prentice Hall; 2008.

[67] Linden W, Earle TL, Gerin W, Christenfeld N. Physiological stress reactivity and recovery: conceptual siblings separated at birth? Journal of Psychosomatic Research 1997; 42(2): 117-35.

[68] Frankenhaeuser M. The psychophysiology of workload, stress, and health: comparison between the sexes. Ann Behav Med 1991; 13:197-204.

[69] Lai JY, Linden WG. Anger expression preferences, and opportunity for anger release determine cardiovascular recovery from anger provocation. Psychosomatic Medicine 2000; 62:648-54.

[70] King AC, Oka RK, Young DR. Ambulatory blood pressure and heart rate responses to the stress of work and care giving in older women. J Geront Med Sci 1994; 49:M239-45.

[71] National Academy of Sciences. Construction Research at NIOSH: Reviews of Research Programs of the National Institute for Occupational Safety and Health. National Research Council; 2008.

Table 1 Pre- work and post-work physiological indices (Mean ± SD)

Parameter	Pre-work	Post-work
Percentage of body fat (%)	17.3 ± 6.1	16.4 ± 5.9
Resting heart rate (bpm)	71.1 ± 5.7	77.7 ± 7.8
Resting diastolic blood pressure (mmHg)	74.2 ± 8.7	79.9 ± 5.6
Resting systolic blood pressure (mmHg)	118.2 ± 7.3	122.8 ± 7.2
Ratings of perceived exertion (RPE)	1.3 ± 0.6	2.9 ± 0.5

Table 2 T-test of core temperature at exhaustion by different fitness groups

Core temperature at exhaustion	PBF	Mean	St. Dev.	t	Sig. (2-tailed)
	8%-14%	38.6	0.037	-5.323	.000
	15%- 27%	38.3	0.095		

Table 3 ANOVA test of heart rate at different levels of alcohol drinking intake

Heart rate	Alcohol drinking habit	Mean	St. Dev.	F	Sig.
Rest	None	80	3.12	27.25	.000
	Occasionally	84	2.21		
	Usually	87	4.12		
Work	None	103	2.16	29.12	.000
	Occasionally	115	2.78		
	Usually	122	3.16		
Recovery	None	86	1.99	28.23	.000
	Occasionally	90	3.15		
	Usually	95	3.26		

Table 4 Pre-work PSI and post-work PSI (each at 5 minutes interval)

No	Pre-work PSI (or PSI $_{min}$)	Post-work PSI							
		5 min	10 min	15 min	20 min	25 min	30 min	35 min	40 min
1	**1.05**	1.42	1.58	1.45	1.35				
2	**2.11**	2.47	2.21	2.37	2.45				
3	**3.19**	4.59	4.20	3.22	3.34	3.69			
4	**1.86**	3.06	2.75	2.59	2.48	2.15	2.02	1.79	1.5
5	**1.49**	1.84	1.8	0.62	0.49	0.68			
6	**0.49**	1.64	1.19	0.80	0.40				
7	**1.15**	3.54	4.59	2.27	1.46				
8	**0.74**	2.23	1.8	1.11	0.83	0.56	0.71		
9	**2.47**	4.22	4.34	3.85	3.67				
10	**2.54**	3.47	3.39	2.84	2.97				
11	**3.21**	3.64	2.57	2.62	2.71				
12	**2.59**	4.69	4.9	4.47	4.34				
13	**2.41**	5.46	4.6	4.17	4.4	3.46	3.01		
14	**1.08**	1.94	1.78						
15	**3.69**	4.34	2.07	3.2	3.21	2.96			
16	**2.26**	3.47	3.39	3.08	3.16	3.03			
17	**2.01**	2.9	1.73	1.85	0.67	0.5			
18	**0.67**	1.79	1.2	0.88					
19	**1.13**	3.1	1.64	1.09					

Table 5 Rate of recovery (%) for construction rebar workers

No.	Rate of recovery (%)							
	5 min	10 min	15 min	20 min	25 min	30 min	35 min	40 min
1	73.9%	66.5%	72.4%	77.8%				
2	85.4%	95.5%	89.0%	86.1%				
3	69.5%	76.0%	99.1%	95.5%	86.4%			
4	60.8%	67.6%	71.8%	75.0%	86.5%	92.3%	100.0%	
5	81.0%	82.8%	100.0%					
6	29.9%	41.2%	60.9%	100.0%				
7	32.5%	25.1%	50.7%	78.8%				
8	33.2%	41.8%	66.7%	89.2%	100.0%			
9	58.5%	56.9%	64.2%	67.3%				
10	73.2%	74.9%	89.4%	85.5%				
11	88.2%	100.0%						
12	55.2%	52.9%	57.9%	59.7%				
13	44.1%	52.4%	57.8%	54.8%	69.7%	80.1%		
14	55.7%	60.7%						
15	85.0%	100.0%						
16	42.0%	66.7%	73.4%	71.5%	74.6%			
17	69.3%	100.0%						
18	37.4%	57.0%	76.2%					
19	36.5%	68.8%	100.0%					

Table 6 Extrapolated rate of recovery (%) for construction rebar workers

No.	Rate of recovery (%)							
	5 min	10 min	15 min	20 min	25 min	30 min	35 min	40 min
1	73.9%	66.5%	72.4%	77.8%	77.0%	78.8%	80.5%	82.3%
2	85.4%	95.5%	89.0%	86.1%	87.9%	87.5%	87.1%	86.6%
3	69.5%	76.0%	99.1%	95.5%	86.4%	100.0%	100.0%	100.0%
4	60.8%	67.6%	71.8%	75.0%	86.5%	92.3%	100.0%	100.0%
5	81.0%	82.8%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
6	29.9%	41.2%	60.9%	100.0%	100.0%	100.0%	100.0%	100.0%
7	32.5%	25.1%	50.7%	78.8%	87.9%	100.0%	100.0%	100.0%
8	33.2%	41.8%	66.7%	89.2%	100.0%	100.0%	100.0%	100.0%
9	58.5%	56.9%	64.2%	67.3%	70.1%	73.5%	76.8%	80.2%
10	73.2%	74.9%	89.4%	85.5%	93.6%	98.8%	100.0%	100.0%
11	88.2%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
12	55.2%	52.9%	57.9%	59.7%	61.0%	62.9%	64.7%	66.6%
13	44.1%	52.4%	57.8%	54.8%	69.7%	80.1%	90.5%	100.0%
14	55.7%	60.7%	65.7%	70.7%	75.7%	80.7%	85.7%	90.7%
15	85.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
16	42.0%	66.7%	73.4%	71.5%	74.6%	86.6%	93.6%	100.0%
17	69.3%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
18	37.4%	57.0%	76.2%	95.7%	100.0%	100.0%	100.0%	100.0%
19	36.5%	68.8%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Average	**58.5%**	**67.7%**	**78.7%**	**84.6%**	**87.9%**	**91.6%**	**93.6%**	**95.1%**

Table 7 Comparison of recovery rates between clinical experiment and field studies

	Recovery rate							
	5 min	10 min	15 min	20 min	25 min	30 min	35 min	40 min
Clinical experiment	46.3%	52.9%	60.1%	68.3%	75.7%	82.3%	90.4%	97.1%
Field studies	58.8%	68.8%	78.1%	84.4%	88.2%	92.1%	93.0%	94.1%
Difference	12.5%	15.9%	18.0%	16.1%	12.5%	9.8%	2.6%	-3.0%

Table 8 Paired correlations of recovery rates between field studies and clinical experiment

Pair	N	Correlation	Sig.
Rate of recovery (field studies) & Rate of recovery (clinical experiment)	8	.945	.000

Table 9 Paired samples test of recovery rates between field studies and clinical experiment

Pair	Paired Differences			t	df	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean			
Rate of recovery (field studies) - Rate of recovery (clinical experiment)	10.550	7.269	2.570	4.105	7	.005

Figure 1 Protocol of the research study

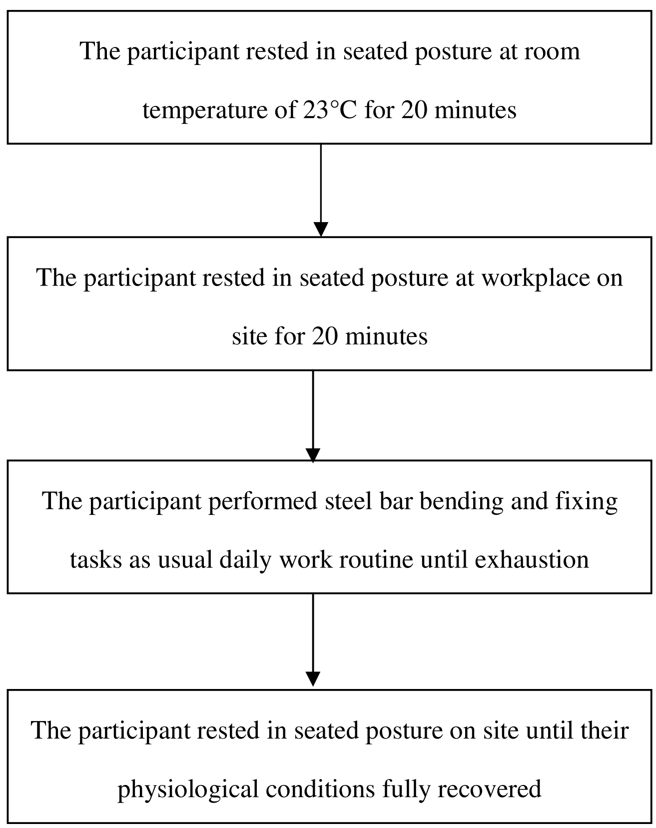

Figure 2 Frequency distribution diagram of WBGT (°C)

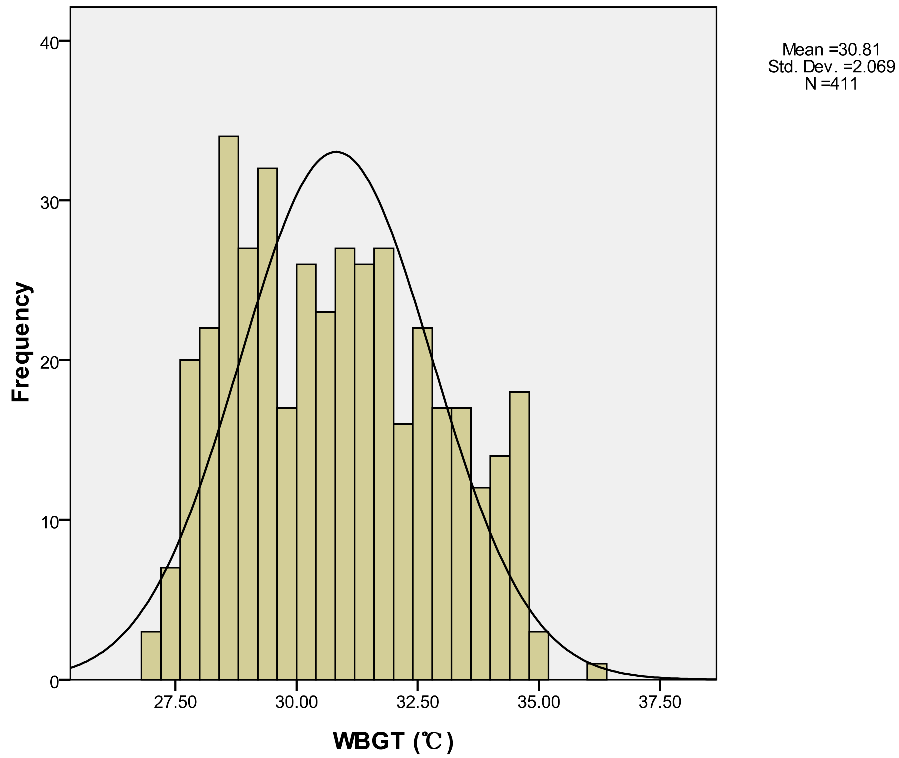

Figure 3 Core temperature at different levels of physiological conditions

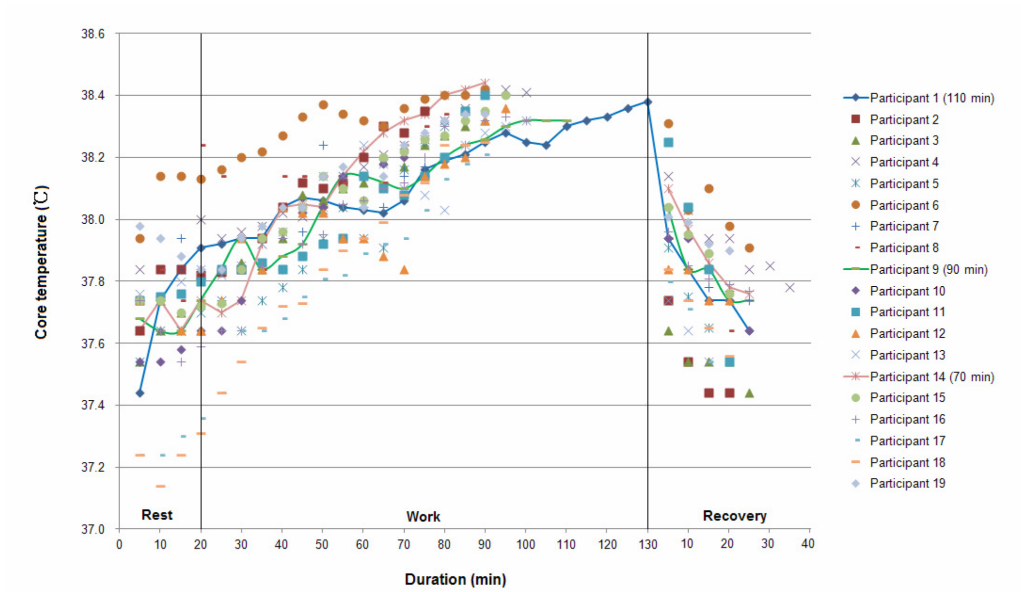

Figure 4 Heart rate at different levels of physiological conditions

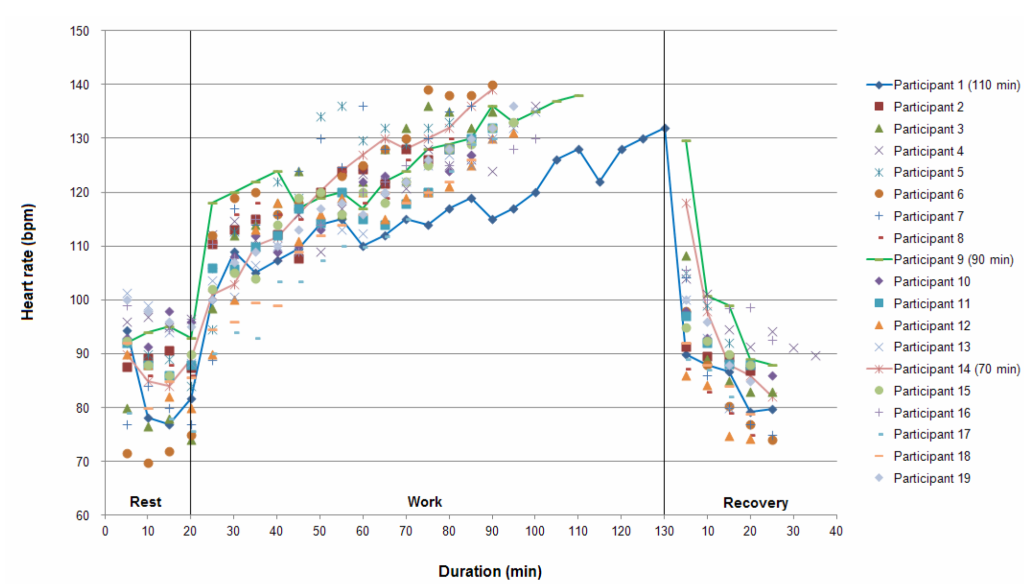

Figure 5 Oxygen consumption at different levels of physiological conditions

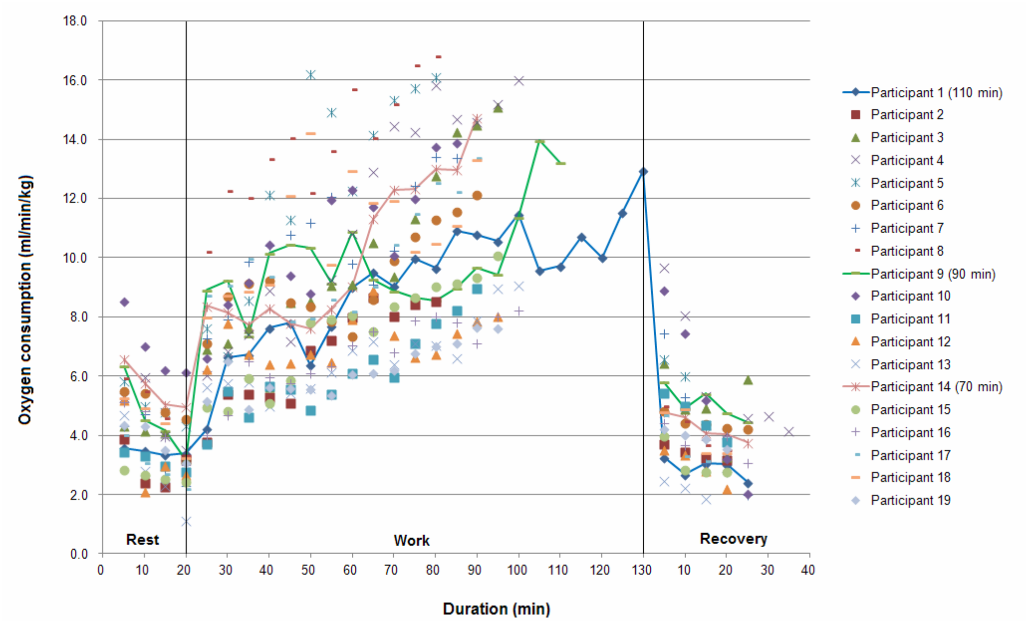

Figure 6 Respiratory exchange ratio (RER) at different levels of physiological conditions

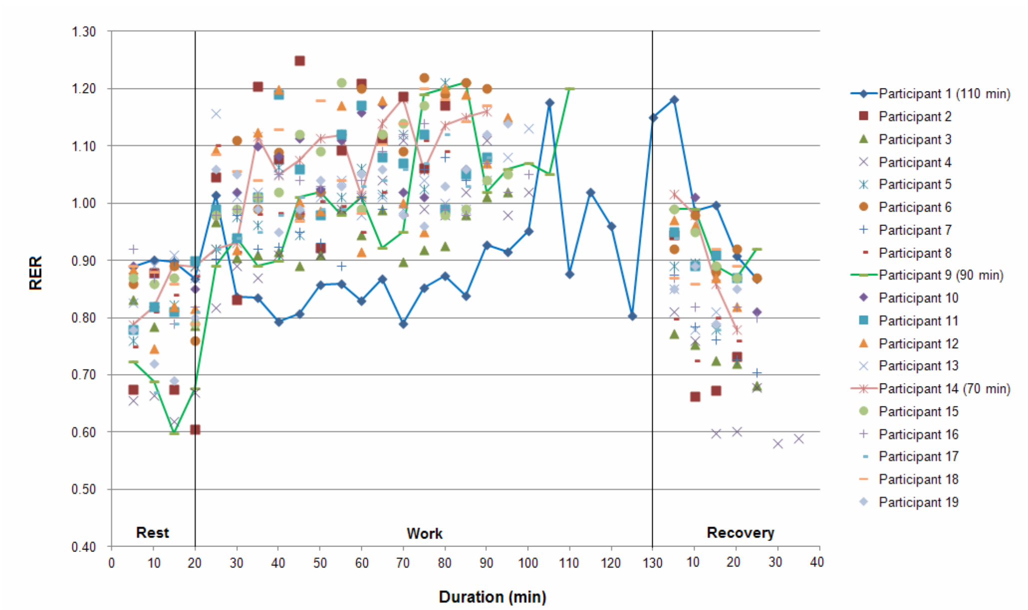

Figure 7 Rating of perceived exertion (RPE) at different levels of physiological conditions

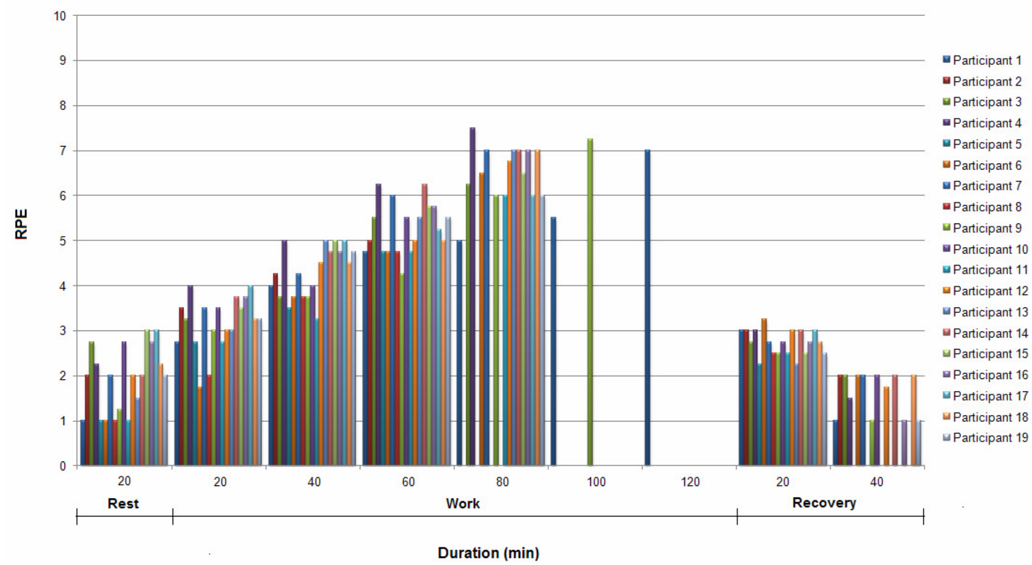

Figure 8 Curve estimation for the rate of recovery for construction rebar workers

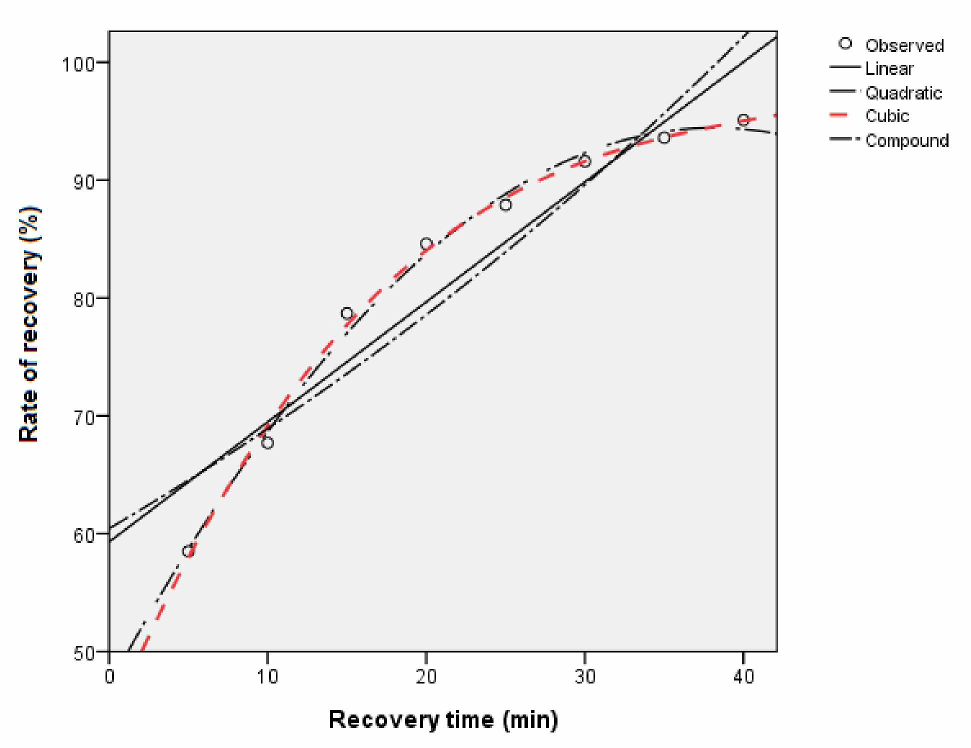

Figure 9 Cumulative curve for determining the optimal recovery time of construction rebar workers