Physiological Demands during Construction Work

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Abstract: Notwithstanding the use of earthmoving equipment, cranes, and other machinery, physically strenuous and demanding tasks remain endemic to the construction industry. This research was motivated by the need to investigate the physical demands of construction work and to evaluate whether these physical demands are excessive. Physiological measures of energy expenditure, including oxygen consumption and heart rate data, were collected for 100 construction workers performing typical construction work. The average oxygen uptake for the measured construction activities was 0.82 $L \cdot min^{-1}$ (± 0.22 $L \cdot min^{-1}$), and the average heart rate for the measured construction activities was 108 beats $\cdot min^{-1}$ (± 17 beats $\cdot min^{-1}$). The measured data were evaluated against published guidelines for acceptable levels of physical performance in industrial settings indicating that a significant number of craft workers (20 to 40%) routinely exceed these physiological thresholds. The results clearly point to the need to promote and apply concepts of work physiology at the workplace to better the occupational health and safety of the construction workforce. This paper developed the foundation for further applied research regarding the physical demands of construction work.

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Introduction

Physically demanding work can lead to physical fatigue, which may lead to decreased productivity and motivation, inattentiveness, poor judgment, poor quality work, job dissatisfaction, accidents, and injuries (Brouha 1967; Janaro 1982; National 2000). Many investigators, dating back to Frederick W. Taylor (the father of scientific management) in the early 1900s, have argued that because physical fatigue affects performance, performance can be improved either by eliminating the causes of physical fatigue or at least by finding ways in which to combat the effects of fatigue. Consequently, understanding the physical demands of construction work is of great importance in protecting the workforce's safety and health and in improving productivity. According to Brouha (1967), such understanding is key to the solution of the problem of what a man can do safely.

Earlier studies on the physical demands of construction activities date back to the 1950s and 1960s. These studies were based on work physiology, and energy expenditure values were collected for various trades (Christensen 1953; Lehmann 1961; Astrand 1967; Durnin and Passmore 1967; Astrand et al. 1968; Hansson 1968). These investigations concluded that accurate assessment of construction activities' physiological demands is particularly difficult. This difficulty was attributed to the variety of individual operations involved in one activity and to the lack of consistency among construction workers in adopting a technique to carry out an activity, let alone its individual operations (Astrand and Rodahl 1986).

Most of these earlier studies focused on young healthy males because historically the construction workforce has been composed primarily of young males. The equipment for measuring energy expenditure was cumbersome during vigorous activities, such that the equipment itself may have limited or interfered with normal work activity. Since the 1960s, the workforce has changed to include more women and older workers, and the work itself has changed. In addition, recent advances in computer, microprocessor, and gas analysis technology enable researchers to efficiently measure metabolic and physiologic response to work in a manner that is nonintrusive to the work itself.

These changes certainly warrant the investigation of the physiological demands of today's construction work performed by today's workforce. Such investigations would identify construction work wherein work physiology-based interventions may be most advantageously applied to reduce the associated physiological demands. Examples of these interventions in construction may involve changing the work methods, including investment in more automated tools and equipment; providing appropriate work-rest cycles; or even adjusting expectations of what workers can reasonably be expected to accomplish.

Unfortunately, work physiology has been neglected in most contemporary construction workforce research. Abdelhamid and Everett (1999) reversed this situation and demonstrated the feasibility of measuring the *in-situ* physical demands of construction activities for a concrete placing and finishing operation using work physiology techniques.

Encouraged by the results of Abdelhamid and Everett (1999), a study was conducted on construction sites to measure the level of physiological effort at which construction workers work and to evaluate if the effort exceeds physiologically based standards and limits. Oxygen uptake (VO_2) and heart rate (HR) data for 100 construction workers from 12 different construction trades were

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collected over a period of 6 months of literally living on construction sites. The trades tested are asbestos workers, bricklayers, carpenters, carpet layers, cement finishers, drywall installers, electricians, glaziers, ironworkers, laborers, pipe fitters, and sheet metal workers. In this paper, measurement results are reported and evaluated based on work severity classification and the potential for long-term physical fatigue.

Background

Work physiology is the scientific discipline concerned with understanding metabolic and physiological responses to manual work. The primary focus of work physiology is to prevent workers from experiencing physical fatigue by reducing the physiological demands of work (Astrand and Rodahl 1986). Work physiology has been used in many industrial settings in performing the following (Wyndham et al. 1962; Aquilano 1968; Chaffin 1972; Garg 1976; Khalil and Ayoub 1976; Krajewski et al. 1979; Janaro 1982; Kilbom 1995):

1. Determine if the physical demand of a specific job exceeds the physical capacities of the work population.
2. Determine if a specific individual is able to perform a certain job.
3. Identify the most demanding tasks to exclude weak workers from performing them.
4. Identify the most demanding tasks so that measures can be taken to make them less demanding.
5. Compare the physical demands of alternative ways of doing the work.
6. Evaluate the dynamic and static components of work.
7. Establish work-rest cycle policies (frequency and duration).
8. Predict metabolic demands under different workloads and workplace layout conditions.

Work physiology methods and principles will be briefly presented in the following sections.

Measuring Physiological Demands

Astrand and Rodahl (1986) outlined the basic tasks in measuring the physiological demands of work as follows:

> A basic task for the work physiologist must be that of measuring the rate at which the work is being done, i.e., the workload, and matching this rate with the worker's ability to perform the work.

Typically, workloads or absolute physiological workloads have been determined by directly measuring mean oxygen uptake and/or heart rate during the performance of actual work. Oxygen uptake data from direct measurements or estimates from heart rate have also been used to indirectly estimate the energy cost of performing various human activities, which in turn is used to assess the potential for physical fatigue. Matching measured absolute workload with a worker's ability to perform work refers to expressing mean oxygen uptake (VO_2) and individual work capacity (expressed as maximum oxygen uptake or $VO_{2\max}$, also known as maximum aerobic capacity) as a ratio, commonly known as relative workload or percentage of $VO_{2\max}$(%$VO_{2\max}$).

Measuring Energy Expenditure

Measuring the energy expended by humans at rest or during work is the cornerstone of many disciplines branching from human physiology (for example, exercise physiology and work physiology). The kilocalorie (kcal) is the unit used for measuring energy. It is defined as the quantity of heat necessary to raise the temperature of 1 kg (1 L) of water 1°C., which is familiar to dieters as the calorie and is equal to about 4 Btu, 1.162 W·h, or 4,186 J. There are two main ways to measure the energy humans expend: direct and indirect calorimetry.

Direct Calorimetry

Human metabolic processes produce heat. The metabolic rate can be estimated by measuring the rate of heat production with a procedure termed ''direct calorimetry'' that can only be performed in a human calorimeter, which is an airtight, thermally insulated chamber. A person can literally live in this chamber, while the heat produced from metabolic processes can be accurately measured during rest or work periods.

Measuring energy expenditure using direct calorimetry can be extremely accurate. However, human calorimeters are very expensive to build and operate and are not portable. These limitations restrict the use of direct calorimetry to academic research performed in laboratory settings.

Indirect Calorimetry

The idea behind indirect calorimetry is quite simple. Since oxygen is used and carbon dioxide is produced during energy-yielding reactions, exhaled air contains less oxygen and more carbon dioxide than inhaled air. The difference in composition between inspired and expired air volumes reflects the body's release of energy through aerobic metabolic reactions. Research has shown that for every liter of oxygen consumed, 4.83 kcal of energy, on average, are produced. Thus, by measuring the rate of oxygen consumption before, during, and after performance of physical activities, the total energy expended by a human can be estimated. It should be noted that the conversion multiplier varies slightly, depending on a physiological attribute termed the ''respiratory quotient.'' This method of estimating energy expenditure from oxygen uptake is referred to as ''indirect calorimetry,'' which, compared to direct calorimetry, provides a reasonably accurate, portable, and relatively inexpensive method of measuring energy expenditure.

Oxygen Uptake Measurements

Measuring oxygen uptake through indirect calorimetry involves two main techniques: closed-circuit and open-circuit spirometry. In a closed-circuit spirometer, the subject re-inhales air that is in the spirometer, hence the name closed-circuit. Closed-circuit spirometry is used mainly to estimate energy expenditure during resting or light-intensity exercise. In addition, closed-circuit spirometers are bulky, which restricts their portability.

In an open-circuit spirometer, the subject inhales ambient air with known concentrations of oxygen, carbon dioxide, and nitrogen. Many open-circuit spirometry devices exist, such as portable spirometers, bag techniques (the most famous is the Douglas bag), and computerized instrumentation. Due to portability, open-circuit spirometry is the most practical and widely used method for measuring oxygen uptake.

Methods for Evaluating Measured Workloads

The physiological response to tasks as a measure of physical demand is only one side of the story—the so-called assessment phase in the literature—the other important side being the evaluation phase. The objective of the evaluation phase is to determine whether the physical demand of a certain task is excessive and whether the worker performing the task may suffer from physical

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Table 1. Severity of Prolonged Physical Work and Cardiovascular Response

Work severity	Mean VO_2 ($L \cdot min^{-1}$)	Mean HR ($beats \cdot min^{-1}$)	Peak VO_2 ($L \cdot min^{-1}$)	Peak HR ($beats \cdot min^{-1}$)
Very light work	NA	NA	Up to 0.5	Up to 75
Light work	Up to 0.5	Up to 90	0.5–1.0	75–100
Moderate work	0.5–1.0	90–110	1.0–1.5	100–125
Heavy work	1.0–1.5	110–130	1.5–2.0	125–150
Very heavy work	1.5–2.0	130–150	2.0–2.5	150–175
Extremely heavy work	Over 2.0	150–170	Over 2.5	Over 175

Note: Source: adapted from Astrand and Rodahl (1986) and Christensen (1983).

fatigue. Workload evaluation techniques include classification of work severity based on published guidelines for oxygen uptake and heart rate (Table 1) and evaluation of physical fatigue potential based on absolute energy expenditure and heart rate values.

Use of Absolute Energy Expenditure as Workload Criterion

The average young adult male, 5 ft 8 in. (173 cm) tall, weighing 160 lb (72.6 kg), in good physical condition, can develop power (energy/time) at the rate of about 5 kcal per minute over an 8 h shift (Astrand and Rodahl 1986; Wickens et al. 1998). A widely used rule of thumb is that activities requiring less than 5 $kcal \cdot min^{-1}$ can be performed continually for a work shift without overly taxing the worker. An activity requiring more than 5 $kcal \cdot min^{-1}$ can be performed for a limited time before the worker needs a rest to recoup energy from stores within the body (Oglesby et al. 1989).

The rest duration required for a worker varies greatly with the intensity and duration of the work cycle itself, as well as with individual differences. According to Brouha (1967) a worker should be allowed to rest until all physiological functions, such as heart rate, blood pressure, oxygen uptake, rate of perspiration, body temperature, chemical composition of the blood and urine, return to *prework* levels. As stated by Brouha (1967), ''*When mechanical work stops, physiological work continues above the resting rate until recovery is complete.*''

Heart Rate as Workload Criterion

Brouha (1967) has suggested that an average HR of 110 $beats \cdot min^{-1}$ over an 8 h shift should not be exceeded by industrial workers. Other researchers have introduced different criteria by distinguishing between HR at rest and HR under physical work. The individual's general fitness level, duration of work, and level of work stress may all affect HR.

Muller (1950) suggested that when the HR remains constant at a prolonged uniform level of work, it may be considered the permanent work HR. Research has shown that if an individual's HR at rest is known, the value of HR for permanent work lies approximately 40 beats above that [HR] (Kuhlmann 1986). Muller (1962) also emphasized the importance of recording the time required for recovery or ''normalization'' of the HR after a work activity has been finished. According to Muller (1962), ''the sum of heart beats during the recovery time (sum of recovery heart rate) is proportional to the degree to which the permanent performance limit has been exceeded.''

Methods

The following sections discuss the equipment and experimental protocol used in this study.

Measuring Equipment

The AeroSport KB1-C ambulatory metabolic analysis, open-circuit spirometery-based system (AeroSport, Inc., Ann Arbor, Mich.) was used for collecting oxygen uptake data. The KB1-C metabolic system contains electronic instrumentation, battery, oxygen and carbon dioxide sensors, and telemetry connections to a microprocessor that permits radio transmissions of up to 300 m (1,000 ft) to a receiver and computer. The KB1-C can be programmed to measure oxygen uptake at 20, 40, or 60-s intervals. Measured oxygen uptake (VO_2) is later converted to energy expenditure by multiplying it, on average, by 4.83 kcal/L.

The KB1-C is compact (7.5×15×5 cm) and lightweight (1.13 kg), making it easy to transport during physical activity. The data module and batteries may be worn with a three-point vest or a contoured waist belt. With this system, subjects are also required to wear a mouthpiece and a nose clip or face mask. In either case, subjects still breathe ambient air. As pictured in Fig. 1, subjects in this study wore a face mask, and a chest vest was used to mount the data collection unit.

Heart rate data were collected using a separate device called the Polar Vantage XL. This heart rate monitor requires subjects to wear a chest band fitted with a sensor/transmitter that measures the HR and transmits it to a microprocessor in a base unit, typically a wrist watch. One of the nice features of the AeroSport KB1-C unit is that it can also record the heart rate transmitted by the Polar Vantage, which allows for the matching of an oxygen uptake reading with a corresponding heart rate.

Experimental Protocol

Choosing the sample size for this study, that is, how many construction workers should be measured, was difficult. Technically, there was no issue since modern instrumentation, such as the

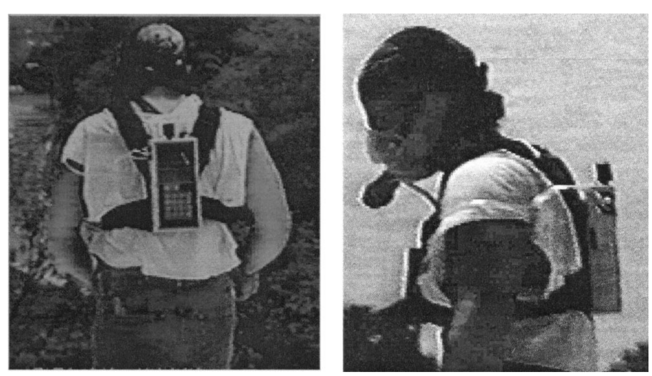

Fig. 1. KB1-C system instrumented on construction worker

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KB1-C system, is capable of measuring the energy expenditure of many workers in a short amount of time and is nonintrusive to work. However, on the one hand, the lessons learned from the pilot study reported by Abdelhamid and Everett (1999) indicated that persuading workers and contractors to participate in this type of research is quite a challenge, especially if a specific trade is to be targeted. On the other hand, the sample size had to be sufficiently large to be representative of a wide range of typical construction work. Therefore, to balance these constraints, 100 subjects were chosen as the target for this research.

Permission to collect physiological data for construction workers was granted by the Health Science Institutional Review Board (IRB File No. 4154) at the University of Michigan, Ann Arbor. Physiological data for construction workers were collected during actual construction work under nonreactive, noninvasive, and naturalistic observations.

For each subject, VO_2 and HR data were collected at 20 s intervals for a period ranging from 30 to 60 min. For each worker, data were collected long enough to ensure that steady-state VO_2 and HR had been reached and/or that several typical work or work-rest cycles had been completed. In addition, the work was videotaped using a conventional camcorder for later documentation of performed work. In most cases, workers indicated that the work they were performing was representative of the whole day. When workers (especially those in skilled trades) indicated that they perform other activities over the course of a day, data were collected for those activities in a separate trial, but for the same worker.

Results

The study resulted in collecting 130 oxygen uptake and heart rate data sets for 100 workers from 12 different trades and video recording 61 h of construction activities. As expected, much effort and time were spent in finding participants on different construction sites. For each worker who participated in this research, the writers had to speak to five workers on average; that is, the success rate in getting workers was about 20%. However, once a ‘‘curious’’ and ‘‘courageous’’ worker agreed to participate, many others followed suit, but typically from the same trade. As a result, the number of activities collected for each trade is different and was a function of which workers agreed to participate in the study. This obviously prevented comparisons among trades. However, even with an equal number of activities in each trade, it is not feasible to compare trades unless the activities collected for the different trades were representative and exhaustive of all activities performed by those trades.

Construction Worker Demographics

The average age for the 100 construction workers is 36.7 years. The age distribution is shown in Fig. 2. Because the current average age of the U.S. construction workforce is 38.5 years (Bureau of Labor Statistics 1997), the data collected for the 100 workers could be used to generalize findings concerning physiological demands to the construction workforce. A comprehensive listing of demographic information regarding the 100 workers, such as age, height, weight, smoking preference, and construction work experience, is provided in Abdelhamid (1999).

All workers were asked to compare (subjectively) how they physically felt when coming to and leaving work with how they felt in general about the physical demands of construction work. This questioning was not pursued on a scientific or systematic basis, and the writers were mainly interested in gaining insight into the workers' general perception of the physical demands of their work. The following statements may represent extreme positions or cases, but they were heard frequently enough to merit considering them as anecdotal evidence of common perceptions about the physical demands of construction work:

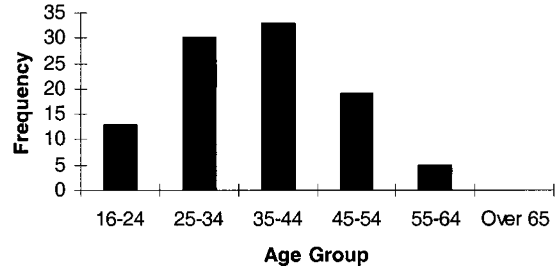

Fig. 2. Histogram for subjects' ages

- ‘‘Tough; I sometimes fall asleep while driving home.’’
- ‘‘Tiring, especially when you go back home.’’
- ‘‘Hardest job, and you go home wanting only to sleep.’’
- ‘‘It's very tough and depends on the day; some are worse than others.’’
- ‘‘Very hard, but it is what we do for a living.’’
- ‘‘Many of my buddies want my job as trim carpenter because it's easier.’’
- ‘‘It varies, but we have to work to get paid.’’
- ‘‘This day is a picnic, compared to working with 180 lb 3/4 in. boards.’’
- ‘‘Kills you’’; ‘‘Very tiring’’; ‘‘Tough.’’

Most of the workers considered themselves in good health. While smoking preferences varied among workers, 90% of the workers indicated they frequently consume alcoholic beverages. Some workers also suffered from various medical problems such as high blood pressure, crushed disc in neck, physical fatigue, high lead levels, shoulder pains, chronic bronchitis, blocked arteries, tennis elbow, tendonitis, and heat strokes.

All workers showed interest in finding out the results of the study, and they all requested reports detailing their energy expenditure and heart rate values. Aside from the study, participants and nonparticipants were quite vocal and expressive of their views toward safety and its future on construction sites. To some, wearing a hard hat and steel-toed shoes is all that safety is about. To others, protective eyeglasses, tag-out lockout procedures, wet-cutting bricks or blocks, confined space permits, equipment shields and safeguards, fall-protection harnesses, ladder and scaffold safety, and so on are ‘‘a no brainer if you ask me, but tell me who follows them?’’

Most of the workers are convinced that safety is only paid lip service and exploited for grandstanding. The workers indicate that safety is applied differently on different sites and ultimately depends on the ‘‘company running the show.’’ The workers believe that if they insisted on following safety rules not sanctioned or deemed OSHA-necessary by an employer, they can then expect not to be called for work the following week. A veteran worker succinctly summarized this situation by saying that ‘‘In construction you have to choose your battles.’’ In general, the workers who participated in the study were a source of inspiration and motivation to continue this work.

Absolute Workloads

Measuring physiological demands (specifically oxygen uptake) for an 8 h work period is impractical for construction activities,

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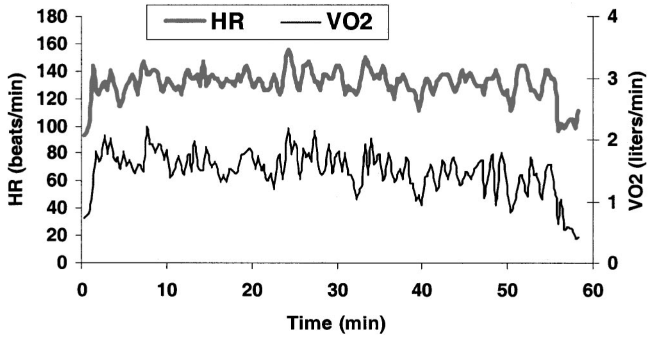

Fig. 3. Sample oxygen uptake and heart rate data for worker 4

Table 2. Summary of Absolute Workloads for Construction Activities

Physiological variable	Average	Standard deviation	Range (minimum–maximum)	Coefficient of variation (COV)
VO_{2avg} ($L\cdot min^{-1}$)	0.82	±0.22	0.41–1.48	0.27
VO_{2peak} ($L\cdot min^{-1}$)	1.40	±0.43	0.58–3.02	0.31
HR_{avg} ($beats\cdot min^{-1}$)	108	±17	69–155	0.16
HR_{peak} ($beats\cdot min^{-1}$)	131	±20	78–189	0.15

especially if measurements are taken in-situ. Therefore, for purposes of reporting the energy expenditure of work and also to perform long-term fatigue evaluations, it was assumed that observed mean and peak workloads for a typical work-rest cycle would occur throughout the day with the same intensity and frequency. In other words it was assumed that collected oxygen uptake and heart rate data represent a typical work-rest cycle and that the worker performs the activity for a full work shift, or up to 8 h (including prescribed break periods and normal work-rest cycles).

As stated earlier, for some workers physiological data were collected more than once, resulting in 130 observed construction activities. To avoid confusion, all measurement results will be reported for the 130 construction activities, unless otherwise noted.

Figs. 3 and 4 show the VO_2 and HR data collected for workers 4 and 78 with respect to time of observations. It can be seen that in periods of work, an increase in HR is followed by an increase in VO_2, while during rest a decrease in HR is followed by a decrease in VO_2, respectively. This display of correlation was similarly observed for all workers. Moreover, both workers reach a certain level of steady state during work periods. However, most construction workers never attained steady state since their work pace fluctuates.

After completing data collection, absolute workloads for construction activities were determined. Absolute workload refers to the mean and peak of the collected oxygen uptake and heart rate data. Peak loads are included as a part of absolute workload since they reflect the physical strain imposed on a worker (Astrand and Rodahl 1986). Other relevant statistical data were determined, such as standard deviation and lowest observed values for oxygen uptake and heart rate.

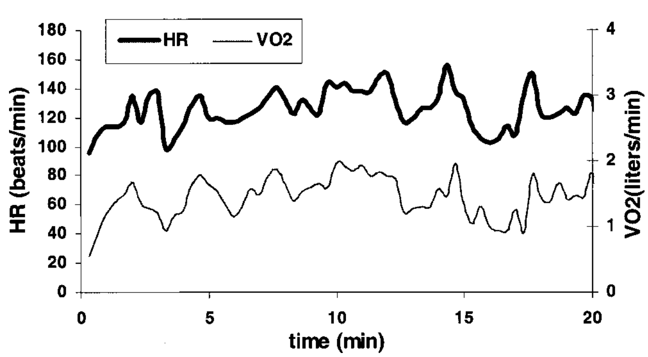

Fig. 4. Sample oxygen uptake and heart rate data for worker 78

Due to space limitations, absolute workloads determined for the 130 construction activities are summarized in Table 2. A coefficient of variation (COV), defined as the ratio between standard deviation and average, is provided in Table 2 to give a measure of the amount of variability relative to the value of the average. To aid in visualizing the physiological data collected, the statistical frequency distributions shown in Figs. 5(a–d) are used. The interested reader is referred to Abdelhamid (1999) for a comprehensive listing of the measured absolute workloads.

Table 3 contains physiological demands sorted by trade and by ascending order of average energy expenditure within each trade. As previously mentioned, energy expenditure is readily determined by multiplying oxygen uptake by 4.83 kcal/L. The physiological demands reported in Table 3 are average energy expenditure, average energy expenditure relative to body weight, and average heart rate. In addition, following each trade's physiological data, an overall average, standard deviation, and coefficient of variation (COV) are provided. The benefit of normalizing average energy expenditure with respect to body weight will be discussed shortly.

It should be noted that in Table 3, the values in the 5th, 7th, and 9th columns were based on all measured observations. These values will be used throughout the remainder of the paper. The 6th, 8th, and 10th columns were determined by ignoring the first and last 2 min of observations. This procedure is recommended so that physiological demands for the work cycle can be determined (Durnin and Passmore 1967).

As can be seen at the end of Table 3, the average energy expenditure and heart rate for all trades, using all observations, were 3.96 $kcal\cdot min^{-1}$ and 108 $beats\cdot min^{-1}$, respectively, with a standard deviation of ±1.05 $kcal\cdot min^{-1}$ and ±17 $beats\cdot min^{-1}$, respectively. Similarly, the average energy expenditure and heart rate for all trades, based on ignoring the first and last 2 min of observations, were 4.05 $kcal\cdot min^{-1}$ and 109 $beats\cdot min^{-1}$, respectively, with a standard deviation of ±1.12 $kcal\cdot min^{-1}$ and ±17 $beats\cdot min^{-1}$, respectively. Without even resorting to a formal statistical test, it is clear that the results are practically the same. Nevertheless, for the sake of physiological "completeness," both numbers are tabulated in Table 3.

It is worth noting that the procedure of ignoring the first and last 2 min of observations in calculating energy expenditure of an activity implicitly assumes that the worker reaches a physiological steady state during the work phase or is continuously working on a task. While a few construction activities may exhibit steady-state data profiles, the majority of construction activities are composed of a number of randomly executed tasks at varying speeds and intensities. Observing no difference between the values reported in Table 3 using either procedure substantiates this argument.

Table 4 provides the maximum and minimum (that is, the range) of weight-corrected average energy expenditures for the construction activities performed by the different trades studied in

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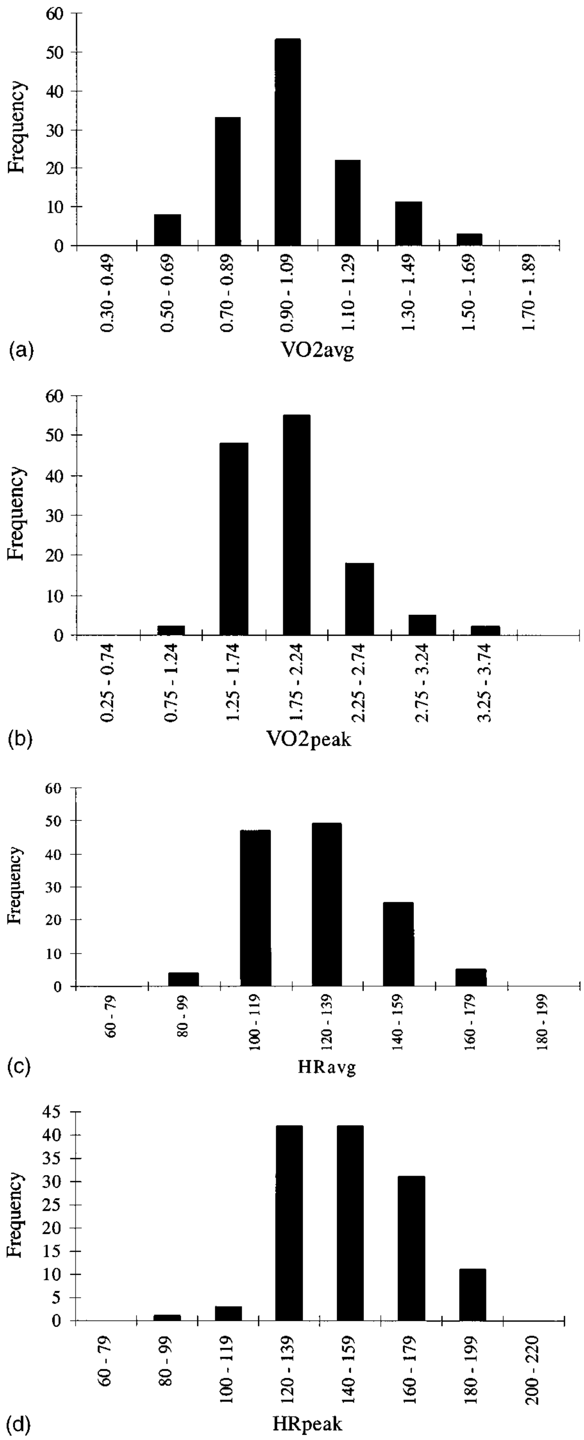

Fig. 5. (a) Frequency distribution for mean oxygen uptake; (b) frequency distribution for peak oxygen uptake; (c) frequency distribution for mean heart rate; and (d) frequency distribution for peak heart rate.

this research. Note that asbestos workers and carpet layers were not included in Table 4 since there was only one worker in each trade.

Before presenting the results of evaluating the measured level of effort relative to physiological based standards and limits, important observations and remarks on the possible inferences from Tables 3 and 4 are in order.

In Table 3, activities from each trade were grouped and ordered according to energy expenditure. This grouping allows pairwise comparisons between different activities within the various trades documented in this research. However, it is important to bear in mind that the data in Table 3 only reflect the physical demands of the construction workers participating in this study.

These workers obviously differed in individual factors such as body dimensions and work factors such as pace of work, amount of work produced, and technique used. While correcting for body weight is simple, it is very difficult—if not impossible—to correct for factors such as pace of work and amount of work produced. Therefore, attempting to infer an overall average energy expenditure value from two or more apparently similar activities within a certain trade, as reported in Table 3, should only be performed after verifying that the activities may be regarded as the same.

Nevertheless, the data given in Table 3 are useful in giving an order of magnitude and range of physical demands that could be expected when performing construction activities *similar* to those described in this study. To illustrate this, consider the information in Table 4 and assume that a person weighing 100 kg is considering bricklaying as a vocation. If this person performs activities similar to those described in Table 3, he or she should expect to have energy expenditures between 2.8 and 5.5 $\mathrm{kcal\cdot min^{-1}}$ ($0.028\ \mathrm{kcal\cdot kg^{-1}\cdot min^{-1}}\times 100\ \mathrm{kg}=2.8\ \mathrm{kcal\cdot min^{-1}}$ and $0.055\ \mathrm{kcal\cdot kg^{-1}\cdot min^{-1}}\times 100\ \mathrm{kg}=5.5\ \mathrm{kcal\cdot min^{-1}}$). Similarly, if this person is considering working as a laborer and performs activities similar to those described in Table 3, then he or she should expect to have energy expenditures between 2.3 and 8.4 $\mathrm{kcal\cdot min^{-1}}$.

Evaluating Construction Physiological Data

As mentioned previously, measuring the physiological demands of work is only one side of the coin; the other important side is evaluation of the physiological demands. In this research, work severity will be evaluated using the criteria in Table 1. Potential for physical fatigue will be evaluated based on the 1 $\mathrm{L\cdot min^{-1}}$ and 110 $\mathrm{beats\cdot min^{-1}}$ limits for mean oxygen uptake and heart rate, respectively.

Evaluation Results

The results for workload severity for the 130 construction activities using Table 1 are summarized in Table 5. The findings based on workload intensity classification results in Table 5 indicate the following:

1. Based on mean oxygen uptake values, 21% of construction workers were classified as performing heavy to very heavy work.
2. Based on peak oxygen uptake values, 41% of construction workers were classified as performing heavy to extremely heavy work.
3. Based on mean heart rate values, 45% of construction workers were classified as performing heavy to extremely heavy work.
4. Based on peak heart rate values, 63% of construction workers were classified as performing heavy to extremely heavy work.

The mean oxygen uptake and heart rate data for the 130 construction activities documented in this research were evaluated for potential for physical fatigue based on the 1 $\mathrm{L\cdot min^{-1}}$ and 110 $\mathrm{beats\cdot min^{-1}}$ limits. Table 6 summarizes the findings of these evaluations for the different trades observed and for the 130 observed construction activities.

The mean absolute workloads reported in Table 6 indicate that about 21 and 45% of construction workers are working at levels

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Table 3. Physiological Demands by construction Trade

Trade	Worker number	Activity number	Activity observed	Average Energy Expenditure (kcal/min)[a]	(kcal/min)[b]	(kcal/kg/min)[a]	(kcal/kg/min)[b]	Average Heart Rate (beats/min)[a]	(beats/min)[b]
Asbestos workers									
	53	81	Insulate duct sections	2.99	3.09	0.048	0.049	99	100
	53	82	Insulate duct sections/clean up	3.48	3.86	0.055	0.061	88	89
Average				3.24	3.48	0.052	0.055	94	95
Standard deviation				0.35	0.54	0.005	0.008	8	8
COV				0.11	0.16	0.10	0.15	0.08	0.08
Bricklayers									
	14	14	Lay bricks	1.98	1.93	0.028	0.028	98	98
	66	95	Grout brick wall and door jambs	2.27	2.27	0.030	0.030	91	91
	69	98	Lay bricks—finish vertical joints	2.56	2.56	0.036	0.036	108	108
	58	87	Install precast lintels	2.70	2.70	0.032	0.032	99	97
	70	99	Install flashing	2.70	2.75	0.034	0.035	106	106
	67	96	Lay bricks and blocks	3.24	3.38	0.031	0.032	111	113
	62	91	Tool brick wall joints	3.43	3.43	0.037	0.037	96	95
	55	84	Lay blocks—grout filling	3.72	3.86	0.041	0.042	93	94
	13	13	Assemble motorized scaffold	3.86	3.91	0.055	0.056	116	117
	56	85	Lay blocks—12″ blocks	4.54	4.83	0.055	0.058	101	104
	68	97	Lay blocks—8″ blocks	4.83	4.93	0.046	0.047	120	121
Average				3.26	3.32	0.04	0.039	104	104
Standard deviation				0.92	1.00	0.01	0.01	9.44	10
COV				0.28	0.30	0.25	0.26	0.09	0.10
Carpenters									
	9	9	Install door accessories	3.04	3.04	0.041	0.041	105	105
	50	76	Align formwork panels	3.19	3.19	0.031	0.031	71	71
	41	79	Install side dowels in formwork	3.24	3.24	0.031	0.031	90	90
	39	60	Install chamfer strips	3.33	3.38	0.037	0.038	107	108
	79	108	Install bracking for formwork	3.57	3.67	0.044	0.045	111	111
	41	55	Remove form ties	3.67	3.48	0.035	0.033	90	90
	41	75	Measure and cut material	3.86	4.15	0.037	0.040	96	97
	74	103	Cut studs	3.86	3.91	0.052	0.052	122	125
	39	47	Place formwork panels-2′×4′	4.01	4.15	0.045	0.046	107	108
	50	72	Remove form ties, wales, bracing	4.15	4.20	0.040	0.040	73	73
	72	101	Assemble interior partitions	4.15	4.06	0.046	0.045	149	149
	75	104	Build interior partitions	4.44	4.59	0.053	0.055	135	136
	77	106	Place formwork panels-2′×6′	4.83	4.83	0.046	0.046	80	80
	73	102	Build exterior walls	5.31	5.55	0.060	0.063	146	148
	80	109	Install bracing for formwork—install posts using sledge hammer	5.41	5.51	0.068	0.070	111	111
	76	105	Build exterior and interior frames	5.80	6.28	0.075	0.082	132	136
	7	7	Install expansion joints	6.04	6.33	0.081	0.085	118	119
Average				4.17	4.33	0.05	0.050	109	109
Standard deviation				0.94	1.05	0.01	0.017	23	24
COV				0.23	0.24	0.30	0.33	0.21	0.22
Carpet layers									
	11	11	Lay carpets	4.59	4.83	0.070	0.074	110	111
Cement finishers									
	82	111	Break off wall ties	2.22	2.32	0.031	0.032	83	84
	81	110	Sand concrete wall	2.32	2.32	0.027	0.027	91	94
	83	112	Patch concrete wall	2.42	2.56	0.032	0.034	88	91
	43	51	Hand floating and troweling	2.66	2.61	0.024	0.024	106	105
	1	1	Machine floating and troweling	2.85	3.04	0.034	0.036	86	87
	2	2	Hand screeding and troweling	5.22	5.31	0.059	0.060	139	140
	8	8	Hand edging and troweling	6.13	6.47	0.073	0.077	155	157
Average				3.40	3.52	0.04	0.041	107	108
Standard deviation				1.59	1.67	0.02	0.020	29	29
COV				0.47	0.48	0.46	0.47	0.27	0.26

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Table 3. (*Continued*)

Trade	Worker number	Activity number	Activity observed	Average Energy Expenditure (kcal/min)[a]	(kcal/min)[b]	(kcal/kg/min)[a]	(kcal/kg/min)[b]	Average Heart Rate (beats/min)[a]	(beats/min)[b]
Drywall installers									
	34	42	Place joint compound	2.90	2.99	0.035	0.036	91	92
	47	64	Mark runner and stud locations	3.19	3.24	0.044	0.045	120	121
	31	38	Install runners to steel beam	3.33	3.43	0.041	0.042	92	93
	12	12	Hang drywall—no lifting	3.38	3.48	0.049	0.050	110	110
	30	37	Carry and cut studs	4.30	4.35	0.045	0.046	97	98
	31	67	Carry drywall	4.30	4.35	0.053	0.054	130	130
	10	10	Cut drywall	4.44	4.69	0.057	0.060	140	141
	47	68	Hang drywall—lifting involved	4.49	4.64	0.062	0.064	138	141
Average				3.88	3.90	0.050	0.050	114	116
Standard deviation				0.65	0.68	0.010	0.009	22	21
COV				0.17	0.17	0.19	0.19	0.19	0.18
Electricians									
	92	121	Install and Carry electrical conduit (motorized scaffold)	2.46	2.42	0.027	0.027	89	81
	97	126	Prepare panel box for mounting	2.95	2.95	0.031	0.031	89	88
	91	120	Install, cut, and carry electrical conduit (motorized scaffold)	2.99	3.04	0.033	0.034	89	91
	100	129	Cut and install electrical conduit	2.99	3.04	0.030	0.031	98	99
	93	122	Install pipe strut racks	2.99	3.04	0.033	0.034	99	99
	94	123	Install electrical conduit	3.48	3.57	0.055	0.057	116	117
	29	36	Install and cut electrical conduit	3.77	3.96	0.052	0.055	109	110
Average				3.09	3.15	0.04	0.038	98	98
Standard deviation				0.42	0.49	0.01	0.012	11	13
COV				0.14	0.16	0.30	0.32	0.11	0.13
Glaziers									
	85	114	Remove window framing	3.62	3.77	0.042	0.044	122	122
	98	127	Install hardware (ground level)	3.86	3.82	0.048	0.047	121	120
	86	115	Remove window framing	4.01	4.01	0.047	0.047	121	122
	99	128	Install hardware (on scaffold)	4.15	4.25	0.048	0.049	117	116
Average				3.91	3.96	0.050	0.047	120	120
Standard deviation				0.23	0.22	0.002	0.002	2	3
COV				0.06	0.06	0.06	0.044	0.02	0.02
Ironworkers									
	49	71	Clean-up (gather tools)	2.61	2.61	0.019	0.019	95	94
	42	50	Layout column footing locations	3.53	3.53	0.041	0.041	90	91
	26	33	Install roof insulation material—one 28.75′ sheet installed	3.53	3.53	0.052	0.052	109	108
	24	28	Connect perlins to steel frame	3.86	3.86	0.049	0.049	107	107
	25	29	Connect perlins to steel frame	3.96	4.06	0.047	0.048	110	110
	42	61	Install tie-wire	4.25	4.72	0.049	0.055	109	111
	38	73	Remove form ties	4.35	4.54	0.053	0.055	94	94
	38	46	Install rebar	4.83	5.07	0.060	0.063	113	114
	25	27	Setup crane to hoist perlins	5.17	5.17	0.062	0.062	134	135
	38	53	Install rebar	5.31	5.46	0.065	0.067	111	111
	42	74	Strip and stack formwork panels	5.31	5.80	0.062	0.067	123	124
	24	26	Assemble window (glass) frame	5.60	5.80	0.071	0.073	132	133
	25	32	Install roof insulation material—four 28.75′ sheets installed	5.65	5.60	0.067	0.066	146	146
Average				4.46	4.52	0.050	0.054	112	113
Standard deviation				0.94	0.97	0.010	0.014	17	17
COV				0.21	0.22	0.25	0.26	0.1	0.1
Laborers									
	5	5	Operate earthmoving equipment	2.22	2.51	0.023	0.026	106	108
	71	100	Haul bricks and blocks (skylift)	2.42	2.27	0.036	0.033	107	107
	44	56	Remove from ties—ten 2′×4′ panels	2.80	2.80	0.028	0.028	107	106

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Table 3. (*Continued*)

Trade	Worker number	Activity number	Activity observed	Average Energy Expenditure (kcal/min)[a]	(kcal/min)[b]	(kcal/kg/min)[a]	(kcal/kg/min)[b]	Average Heart Rate (beats/min)[a]	(beats/min)[b]
	57	86	Mason tending—masons installing precast lintel at ground level	3.19	3.14	0.037	0.037	98	99
	45	59	Build column footing formwork	3.24	3.28	0.043	0.044	116	116
	54	83	Mason tending—masons laying blocks	3.43	3.62	0.034	0.036	87	90
	40	54	Remove stakes	3.43	3.48	0.038	0.039	124	125
	61	90	Mason tending—masons installing wooden arch on 3rd floor window	3.62	3.57	0.052	0.051	94	93
	84	113	Place concrete—holding concrete chute	3.62	3.57	0.039	0.038	101	101
	88	117	Clean-up—sweep 330 sq ft	3.62	3.67	0.052	0.053	115	115
	87	116	Clean-up—sweep 345 sq ft	3.77	3.86	0.044	0.045	94	94
	46	58	Remove form ties and strip panels	3.77	3.96	0.049	0.051	137	137
	45	57	Remove form ties—five 2′×4′ panels in very tight space	3.86	4.01	0.052	0.053	131	132
	40	48	Carry tools and materials	3.86	3.82	0.043	0.042	131	130
	3	3	Operate concrete buggy	4.30	4.35	0.055	0.056	113	112
	46	62	Stack formwork panels—25 2′×4′ panels while walking 30′	4.54	4.83	0.059	0.063	129	130
	65	94	Erect scaffolding	4.83	5.07	0.071	0.075	123	123
	45	63	Stack formwork panels—20 2′×4′ panels while walking 40′	5.31	5.55	0.071	0.074	117	118
	6	6	Place concrete—come along	5.99	6.33	0.075	0.080	109	111
	60	89	Mason tending and scaffold removing	6.42	6.62	0.079	0.082	142	144
	78	107	Formwork carpenter tending	6.91	7.10	0.065	0.067	126	127
	4	4	Clean-up—gather and carry material to dump truck	7.15	7.39	0.084	0.087	131	132
Average				4.20	4.31	0.051	0.053	115	116
Standard deviation				1.38	1.46	0.017	0.018	15	15
COV				0.33	0.34	0.33	0.34	0.1	0.1
Pipe fitters									
	64	93	Install vents for toilet assemblies—one vent	2.70	2.70	0.039	0.039	95	95
	90	119	Install pipes and hangers—cutting hangers and getting tools	2.99	2.99	0.038	0.038	93	93
	89	118	Install pipes and hangers	3.09	3.09	0.022	0.022	114	115
	23	23	Install vents for toilet assemblies—two vents	3.19	3.19	0.049	0.049	95	95
	32	39	Install pipes and soldering	3.24	3.19	0.038	0.037	96	95
	27	40	Solder pipes	3.24	3.28	0.041	0.042	126	126
	21	21	Install toilet assembly	3.33	3.28	0.036	0.035	96	95
	27	34	Install hangers and insulation	3.43	3.57	0.043	0.045	127	128
	51	77	Cut, thread, and file pipe ends	3.57	3.67	0.040	0.041	118	119
	22	22	Install hangers	3.72	3.77	0.033	0.033	93	93
	52	79	Thread and file pipes—4′ long 1″	3.72	3.77	0.030	0.031	103	103
	32	70	Install pipe	3.86	3.86	0.045	0.045	136	136
	63	92	Install vents for toilet assemblies—two vents	3.91	4.01	0.052	0.053	87	88
	35	43	Adjust sprinkler head	4.06	4.25	0.053	0.055	106	109
	15	30	Solder valves on pipe	4.11	4.25	0.048	0.049	105	104
	51	80	Install pipes and sprinkler heads	4.15	4.25	0.046	0.047	114	114
	52	78	Install sprinkler fittings	4.20	4.35	0.034	0.036	102	102
	32	52	Install PVC connections	4.20	4.25	0.049	0.049	106	104
	95	130	Install insulation material	4.35	4.70	0.048	0.052	103	105
	21	31	Install and cut hangers	4.54	4.69	0.049	0.050	100	101
	15	15	Clean-up activities	4.59	4.73	0.053	0.055	102	103
	19	19	Install hoist	4.64	4.83	0.051	0.053	96	97
	95	124	Cut and sand pipe ends	5.31	5.96	0.058	0.066	111	114
	96	125	Weld (arc) elbow to pipe	5.31	5.31	0.034	0.034	109	106

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Table 3. (*Continued*)

Trade	Worker number	Activity number	Activity observed	Average Energy Expenditure (kcal/min)[a]	(kcal/min)[b]	(kcal/kg/min)[a]	(kcal/kg/min)[b]	Average Heart Rate (beats/min)[a]	(beats/min)[b]
	59	88	Cut PVC pipe	5.46	5.75	0.060	0.063	99	100
	19	24	Cut hangers and pipes	5.80	6.04	0.064	0.067	93	94
	36	44	Thread and file pipes—6′ long 4″	6.09	6.28	0.049	0.051	115	116
Average				4.10	4.19	0.044	0.045	105	105
Standard deviation				0.89	0.95	0.009	0.010	12	12
COV				0.22	0.23	0.22	0.23	0.1	0.1
Sheet metal workers									
	28	35	Assemble damper sections	2.42	2.42	0.031	0.031	100	99
	28	66	Carry duct sections—12 30 lb sections moved 40′ (one at a time)	2.80	2.95	0.035	0.037	94	95
	16	16	Assemble damper sections	3.38	3.38	0.030	0.030	97	97
	17	17	Install hangers	3.67	3.72	0.041	0.042	87	87
	17	25	Unload and assemble duct section	3.82	3.96	0.043	0.044	94	95
	20	20	Assemble and seal duct sections	4.06	4.06	0.050	0.050	69	69
	48	69	Install ATF clips on duct sections	4.06	4.11	0.039	0.039	111	112
	33	41	Install access doors and dampers	4.20	4.44	0.044	0.047	110	113
	48	65	Assemble duct sections	4.35	4.40	0.042	0.043	118	118
	37	45	Carry duct sections—4 30 lb sections 1st to 3rd floor (one at a time)	4.97	5.12	0.065	0.067	136	137
	18	18	Hoist and seal duct sections	5.41	5.46	0.050	0.051	104	104
Average				3.92	4.00	0.043	0.044	102	102
Standard deviation				0.87	0.88	0.009	0.010	17	18
COV				0.22	0.22	0.23	0.24	0.17	0.17
All trades									
Average				3.96	4.06	0.046	0.048	108	109
Standard deviation				1.05	1.12	0.013	0.014	17	17
COV				0.26	0.28	0.29	0.30	0.16	0.16

[a]All data.

[b]All data but ignoring first and last 2 min of observation.

exceeding the 1 $L \cdot min^{-1}$ for VO_2 and the 110 $beats \cdot min^{-1}$ for *HR* thresholds, respectively. Such levels of work are considered fatiguing for a work shift or more (Lehmann 1961; Brouha 1967; Astrand and Rodahl 1986; Kilbom 1995). These standard limits are based on an average young (25 year old) adult male in good physical condition. Thus, if corrected for age and other factors if possible, the percentage of workers working at fatiguing levels would most definitely be higher than reported.

As previously mentioned, the age distribution for the 100 construction workers studied in this research appears to conform to that of the entire U.S. construction workforce. Consequently, it is possible to consider the 100 construction workers studied as a representative sample of the construction workforce. And since there are approximately 8.45 million construction workers in the United States (National 2000), the 21 and 45% reported represent a significant number of workers (between 1.8 and 3.4 million) who are working at fatiguing levels based on contemporary physiological standards.

The results based on contemporary physiological standards also indicate that construction workers may be facing more problems with cardiovascular responses than with energy demands. These problems could be reflecting heat stress exposure, heavy static exertions, and/or general health problems.

Table 4. Range of Energy Expenditure by Construction Trade

Trade	Range of average energy expenditure ($kcal \cdot kg^{-1} \cdot min^{-1}$)
Bricklayer	0.028–0.055
Carpenter	0.031–0.081
Cement finisher	0.027–0.073
Drywall installers	0.035–0.062
Electrician	0.027–0.055
Glazier	0.042–0.048
Ironworker	0.019–0.071
Laborer	0.023–0.084
Pipe fitter	0.022–0.064
Sheet metal worker	0.030–0.065

Table 5. Workload Severity Classification for Observed Construction Activities

Workload	Performance Percentage of Construction Workers VO_{2avg} (%)	VO_{2peak} (%)	HR_{avg} (%)	HR_{peak} (%)
Very light	NA	1.7	NA	0
Light	7.4	15.3	14.5	5.7
Moderate	72	41.7	40.3	31.8
Heavy	20.5	33.1	35.4	44.9
Very heavy	0.1	7.7	9.1	16.2
Extremely heavy	0	0.5	0.7	1.4

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Table 6. Absolute Workload Evaluations by Trade

Trade	Observed activities	Percentage of Workers Exceeding: $1\ L\cdot min^{-1}$ for VO_{2avg} (%)	Percentage of Workers Exceeding: $110\ beats\cdot min^{-1}$ for HR_{avg} (%)
Asbestos workers	2	0	0
Bricklayer	11	9	27
Carpenter	16	31	56
Carpet layers	1	0	100
Cement finisher	7	29	29
Drywall installers	9	0	44
Electrician	7	0	14
Glaziers	4	0	100
Ironworker	13	46	54
Laborer	22	27	59
Pipe fitter	27	30	26
Sheet metal workers	11	18	36
All trades	130	21	45

Conclusions

This paper reported the physiological demands of a large number of construction activities. The average oxygen uptake for the measured construction activities was $0.82\ L\cdot min^{-1}$ ($\pm 0.22\ L\cdot min^{-1}$). The average heart rate for the measured construction activities was $108\ beats\cdot min^{-1}$ ($\pm 17\ beats\cdot min^{-1}$). This information provides a sounder base for any conclusions or inferences made concerning the physiological demands of construction work performed by today's construction workforce. The paper also presented a comprehensive evaluation of absolute physiological demands based on standard work severity tables and accepted physiological limits for avoiding long-term physical fatigue.

The findings of this research reveal that based on two physiological indicators of workload—oxygen uptake and heart rate—construction work is classified as moderate to heavy work. Evaluations of workloads reveal that a significant number of craft workers (20 to 40%) routinely exceed generally accepted physiological thresholds for manual work. These workers can become physically fatigued, which may lead to decreased productivity and motivation, inattentiveness, poor judgment, poor quality work, job dissatisfaction, accidents, and injuries.

One important implication extending from the results of this study concerns the need to change the underlying philosophy governing the approach to safety and health in construction today. This change is possible through promoting and applying concepts of ergonomics and work physiology at the workplace. In doing so, many improvements will find their way to the occupational health and safety of the construction workforce.

This research contributes greatly to the state of knowledge about the physiological demands of construction work. The methods described in this research have widespread applications in identifying excessively demanding construction tasks so the work can be better matched to the abilities of the workers. The research described in this paper has developed the foundation for further academic and practical research regarding the physical demands of construction work.

Additional research is needed to assess the physical demands of other types of work and to investigate how physical demands will affect the changing workforce. This will assist labor and management to identify opportunities to reduce physical demands and physical fatigue and cooperate in introducing changes in work procedures and methods to accommodate the abilities of all workers.

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