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Evaluation of physiological metrics as a real-time measurement of physical fatigue in construction workers: State-of-the-Art Reviews

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Abstract

Physical fatigue is a major health and safety related problem among construction workers. Many previous studies relied on interviews and/or questionnaire to assess physical fatigue in construction workers. However, these traditional methods are not only time consuming but also limited by recall bias. To overcome these limitations, many researchers have used physiological metrics (e.g., heart rate, heart rate variability, skin temperature, electromyographic activity, and jerk metrics) to measure real-time physical fatigue. While physiological metrics have shown promising results for real-time assessments of physical fatigue, no state-of-the-art review has been conducted to summarize various physiological metrics in measuring physical fatigue among construction workers. Therefore, the current state-of-the art review aimed to summarize existing evidence regarding the use of physiological metrics to measure physical fatigue of construction workers in real-time. This review used systematic searches to identify relevant studies and critically appraised the application of physiological metrics in measuring physical fatigue of construction workers. First, it summarized the application of various physiological metrics for real-time measurement of physical fatigue in construction workers. Second, various wearable sensing technologies for measuring physiological metrics were identified. Third, this review discussed the potential challenges for applying physiological metrics to measure physical fatigue. Finally, future research directions to advance the development and adoption of various physiological metrics to monitor and mitigate physical fatigue in construction workers were discussed.

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Introduction

Fatigue can be defined as "a reduction in physical and/or mental capability as the result of physical, mental, or emotional exertion which may impair nearly all physical abilities including: strength; speed; reaction time; coordination; decision making; or balance" (International Maritime Organization, 2001). While some authors suggested that fatigue is unidimensional in nature (Michielsen et al., 2004), others described it as a combination of physical and mental fatigue (Grandjean, 1979). Physical fatigue occurred after prolonged physical workloads can reduce an individual's capacity to perform physical work efficiently (Gawron et al., 2001). Similarly, mental fatigue occurs after prolonged mental workloads and may lead to reduced behavioral and cognitive performance (Boksem et al., 2005; Boksem and Tops, 2008). While mental fatigue is known to be associated with impaired physical performance (Marcora et al., 2009), the intensity of physical activity has differential effects on mental fatigue. Specifically, light physical activities may improve cognitive function, whereas heavy physical activities may impair cognitive performance (Davey, 1973); this indicates a complex relationship between physical and mental fatigue. Additionally, mental fatigue is more relevant to industries that require workers to be mentally active and alert, such as long-distance driving (Tan et al., 2013), airport luggage screening (Basner and Rubinstein, 2011), or nurses working long shifts (Geiger-Brown et al., 2012). However, since most construction workers (such as manual laborers) may not require a high level of mental alertness (Aryal et al., 2017), the current review focused on the discussion of various potential real-time monitoring of physical fatigue in construction workers.

Physical fatigue is widely prevalent among construction workers given their job nature, which often involves outdoor work in a harsh environment, manual labor, and physical intensive repetitive tasks. Adverse effects of physical fatigue on health and safety of construction workers have been well documented in the literature (Swaen et al., 2003; Wu et al., 2017; Umer et al., 2018a). For example, prolonged physical fatigue may lower immunity and causes chronic fatigue syndrome (Afari and Buchwald, 2003; Evengard et al., 2008). Similarly, statistics indicated that 33% of all work-related musculoskeletal injuries and disorders in the US construction industry were attributed to fatigue and overexertion (BLS, 2016). Studies in the oil and gas construction industry (Chan, 2011), as well as the building construction industry (Wong et al., 2004; Adane et al., 2013) have also found physical fatigue as a major cause of work-related accidents. As such, it is of paramount importance to detect the presence of physical fatigue in construction workers in the field so that timely interventions (e.g., breaks) can be introduced (Umer et al., 2017a).

Early detection and real-time monitoring of physical fatigue play vital roles in the construction industry, especially when the industry is facing severe labor challenges in many parts of the world such as high labor wages, manpower shortages, and an ageing workforce (Yu et al., 2019). A previous review has reported that approximately 44% and 12% of the workforce in the Hong Kong construction industry were older than 50 and 60 years, respectively (Ng and Chan, 2015). Older construction workers are more prone to develop physical fatigue than their younger counterparts due to the ageing-related reduction in muscle strength and physical work capacity (Faulkner et al., 2007; Kenny et al., 2008; Umer et al., 2018b). Additionally, many developed countries/cities such as the United Kingdom, Singapore, Hong Kong, and Australia are facing manpower shortages in the construction industry because of ageing workers and the reluctance of younger people in joining the construction workforce (Ducanes and Abella, 2008; Sing et al., 2012). For example, the Construction Industry Council of Hong Kong has predicted a significant shortfall of skilled construction workers during 2017 to 2021 (Construction industry council, 2016). To overcome these distressing challenges in the construction industry, it is essential to effectively monitor and manage physical fatigue in construction workers to ensure a more sustainable and productive workforce for the industry in the future.

There are many ways to measure physical fatigue in construction workers. They can be classified into subjective measurements and objective measurements. These methods have pros and cons.

Traditional Subjective Physical Fatigue Assessments

In early 90s, various subjective questionnaires were developed to quantify physical fatigue in the general population (Lee et al., 1991; Chalder et al., 1993). Later, many constructions-related studies have developed various subjective questionnaires to measure workload or physical fatigue in construction workers (Chan et al., 2012; Fang et al., 2015; Mitropoulos and Memarian, 2013; Yi et al., 2016; Zhang et al., 2015). However, since no standardized physical fatigue assessment scale has been developed, different studies used different scales to assess physical fatigue (Zhang et al., 2015), preventing comparisons of findings across studies. Although the cost of using subjective questionnaires is low, it is inconvenient/infeasible to administer questionnaires on construction sites. This method is also subject to recall bias. Importantly, these questionnaires cannot assess real-time physical fatigue with minimal interference to ongoing construction activities.

Real-Time Approaches to Assess Physical Fatigue

To overcome these limitations, some researchers have attempted to use various physiological metrics such as heart rate (HR), heart rate variability (HRV), skin temperature, electromyography (EMG), and jerk metrics to monitor real-time fatigue during construction-related activities (Abdelhamid and Everett, 2002; Cifrek et al., 2009; Chan et al., 2012; Gatti et al., 2014; Wong et al., 2014; Yi et al., 2016; Aryal et al., 2017; Umer et al., 2017b; Ueno et al., 2018; Zhang et al., 2018, 2019; Anwer et al., 2020). For example, Yi et al. (2016) developed an automatic assessment and early fatigue warning system for construction workers based on: (a) Wet Bulb Globe Temperature measurements on construction sites; (b) work duration and activities; (c) personal and demographic characteristics of workers (i.e., age, weight, height, smoking, and alcohol drinking habit); and (d) real-time HR monitoring. They used an artificial neural network (ANN) approach to identify heat strain/fatigue in construction workers. Similarly, Aryal et al. (2017) developed a fatigue model using a machine learning approach to detect and monitor physical fatigue in construction workers based on skin temperature and HR. Since HR and skin temperature are considered as important physiological metrics to assess physical strain during physical exercise (Cuddy et al., 2013), multiple studies have used these metrics to monitor physical fatigue during physically demanding construction activities (Abdelhamid and Everett, 2002; Chan et al., 2012; Gatti et al., 2014; Ueno et al., 2018; Wong et al., 2014; Anwer et al., 2020).

Other physiological metrics, such as EMG activity of muscle and jerk (the time derivative of acceleration) during tasks, have also been used to assess workers' fatigue. Continuous monitoring of muscle EMG activity (a proxy to measure muscle activity) can reveal local muscle fatigue during work (Cifrek et al., 2009; Umer et al., 2017b). Surface EMG has been used in prior laboratory studies to detect real-time muscle fatigue (Karlsson et al., 2000; Felici et al., 2001; Clancy et al., 2002; Antwi-Afari et al., 2017, 2018). Likewise, Zhang et al. (2018) used inertial measurement unit (IMU) sensors to measure jerk to indirectly detect physical fatigue during a repetitive bricklaying task. Since physical fatigue adversely affects movement control and movement quality, workers with fatigue demonstrate increased jerk values (Zhang et al., 2019).

Although the assessment of these physiological metrics may help detect real-time physical fatigue in construction workers (Wang et al., 2015; Awolusi et al., 2018; Ahn et al., 2019), no state-of-the-art review has summarized various physiological metrics in measuring physical fatigue in these workers. Therefore, the current state-of-the-art review aimed to: (1) summarize various physiological metrics that have the potential to measure real-time physical fatigue in construction workers; (2) summarize commercially available wearable sensing technologies for measuring relevant physiological metrics; (3) discuss potential challenges for using physiological metrics to measure physical fatigue in real-time; and (4) provide future research directions to advance the development and use of various physiological metrics to better monitor and mitigate physical fatigue among construction workers.

Research Methods

The research method section is divided into three subsections namely: literature search, selection criteria, and data extraction.

Literature Search

This review used a systematic approach to search relevant articles, and critically appraised the applications and features of different wearable sensing technologies, as well as summarized challenges of using physiological metrics to measure physical fatigue in construction workers. Five electronic databases (i.e., PubMed, Medline, CINAHL, EMBASE, and Web of Science) were searched from their inception to July 25, 2020. The first four databases contain many fatigue or ergonomic-related publications, while the Web of Science is a multidisciplinary database that contains construction-related journals (Gusenbauer and Haddaway, 2020). For instance, the web of science covers more than 34,000 journals and over 155 million of records. Only English language publications were retrieved. The major keywords (including fatigue, physiological measures, heart rate, heart rate variability, skin temperature, electromyographic activity, jerk metric, and construction workers) as well as their related derivatives were used for the search. **Table 1** details the search strategies used in this review.

Selection Criteria

Relevant articles were included for review based on the criteria: (1) population: construction workers; (2) outcome variables: physiological measures (e.g., heart rate, heart rate variability, skin temperature, EMG activity, and jerk metrics) and physical fatigue; and (3) types of study: observational and experimental studies. Studies were excluded if outcomes related to physical fatigue or physiological measures were not reported. Additionally, case reports, newsletters, theses, commentaries, conference proceedings, and grey literature were excluded.

Data Extraction

Two reviewers (SA and MA) completed the screening of titles and abstracts according to the selection criteria. Relevant full-text articles were then retrieved and reviewed by the two independent reviewers. Any disputes between the two reviewers were then resolved by a third reviewer (AW). Relevant data were extracted from the included studies: authors/year, country, population, study design, sample size, type of physiological measures, physical fatigue protocol, instrumentation used, results, and conclusions.

Results

The results section is divided into two subsections namely: (1) characteristics of the included studies; and (2) analysis of physiological metrics to measure real-time physical fatigue in construction workers. The first subsection delineates the characteristics of the included studies. The second subsection details the analysis of physiological metrics under four sub-subsections (e.g., cardio-vascular metrics, thermoregulatory metrics, EMG metrics, and jerk metrics).

Characteristics of the included studies

Of the 324 identified studies, 160 duplicates were removed (**Fig 1**). Twenty-three studies involving 1,015 participants were included in this review. The characteristics of the included studies (including the location where each study was conducted, types of studies (e.g., laboratories or field studies), participants' demographics, types of physiological metrics (e.g., HR, HRV, skin temperature, EMG, Jerk metric), and types of subjective and objectives tools used for validation) are shown in **Table 2**. Specifically, the included studies were conducted in nine regions, including Canada, China, Czech Republic, Hong Kong, India, Latvia, Taiwan, United Arab Emirates, and the USA.

Thirteen field studies and ten laboratory studies (task simulation) were included. The mean age of participants ranged from 26.4 to 45 years. Two included studies only reported the age ranges of their participants (between 20 and 24 years old) (McDonald et al., 2016; Calvin et al., 2016). Most of the included studies used HR metric (19 studies), five study used skin temperature, four studies used EMG metric, and only one study used jerk metric to measure physical fatigue (Figure 2). Physical fatigue was verified by the subjective feedback of the participants. In particular, seven and three included studies used the rating of perceived exertion (RPE) scale (Borg 6-20 scale) (Roja et al., 2006; Li et al., 2009; McDonald et al., 2016; Aryal et al., 2017; Yin et al., 2019; Umer et al., 2020; Anwer et al., 2020) and Borg CR-10 scale (Chan et al., 2012; Wong et al., 2014; Calvin et al., 2016) to report self-perceived physical fatigue, respectively. Seven included studies used researcher-designed, self-reported questionnaires to quantify physical fatigue (Abdelhamid and Everett, 1999, 2002; Hsu et al., 2008; Chang et al., 2009; Mehta et al., 2017; Lee et al., 2017; Tsai, 2017), while six included studies simply asked the participants for the presence of fatigue (Anton et al., 2005; Bates and Schneider, 2008; Maiti, 2008; Das, 2014; Jankovský et al., 2018; Zhang et al., 2019).

Heart rate, HRV, skin temperature, surface EMG, and jerk metrics were used as a proxy to objectively measure physical fatigue (**Fig 2**). Ten included studies used various chest band model devices to monitor HR (Abdelhamid and Everett, 1999, 2002; Anton et al., 2005; Roja et al., 2006; Bates and Schneider, 2008; Maiti, 2008; Chang et al., 2009; Li et al., 2009; Chan et al., 2012; Wong et al., 2014). One study manually calculated HR using radial or carotid pulses (Das, 2014), while seven studies used different wearable devices to measure HR (Hsu et al., 2008; Aryal et al., 2017; Mehta et al., 2017; Lee et al., 2017; Jankovský et al., 2018; Yin et al., 2019; Umer et al., 2020; Anwer et al., 2020). Two studies used photo plethysmography-based wearable sensors to measure heart rate variability (Lee et al., 2017; Tsai, 2017). To measure the skin temperature, infrared temperature sensors (Chan et al., 2012; Aryal et al., 2017), wearable sensors (Mehta et al., 2017; Umer et al., 2020), and tympanic thermometers were commonly used (Bates and Schneider, 2008). Similarly, different models of surface EMG devices were used to measure the root mean square amplitude and median frequency of EMG signals in the included studies to assess muscle fatigue during construction tasks (Anton et al., 2005; McDonald et al., 2016; Calvin et al., 2016; Yin et al., 2019). Additionally, wearable IMU-based motion capture systems were used to measure the jerk metric in one study (Zhang et al., 2019).

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Analysis of physiological metrics to measure real-time physical fatigue in construction workers

Cardio-vascular metrics

Heart rate is the most commonly used physiological measure to monitor physical exertion in construction workers (Abdelhamid and Everett 2002; Chan et al. 2012; Gatti et al. 2014; Wong et al. 2014; Ueno et al. 2018; Anwer et al., 2020). Cardiovascular responses to physical exertion depend on multiple factors, including the intensity, duration, and frequency of physical exertion, as well as the working environment (Burton et al., 2004). During physical exertion, the cardiovascular load increases as muscle contraction increases. The heart needs to pump more blood around the body (Burton et al., 2004). The increased demand of blood flow to muscles requires an increased cardiac output. Since the heart cannot increase its stroke volume instantaneously, only heartbeat can be increased to improve blood transportation. Therefore, average HR is a good indicator of physical stress and workload (Wickens et al., 2004; Zhu et al., 2017). In fact, 19 out of 23 included studies in the current review used HR as a proxy to measure physiological demands during construction tasks. Lifting and lowering from floor-to-floor resulted in a higher HR as compared to other heights of lifting and lowering (Li et al., 2009). Likewise, Li et al. (2009) reported a higher HR for a lifting task performed twice a minute as compared to once a minute. Alferdaws and Ramadan (2020) also found that the HR during high frequency lifting was significantly higher than that during low frequency lifts. In fact, previous studies have shown a positive relationship between HR and lifting frequency (Hafez and Ayoub, 1991; Chen et al., 1992; Al-Ashaik et al., 2015; Ghaleb et al., 2019). The work-related increases in HR would decrease as the workload decreases (Jankovský et al., 2018). More recently, Anwer et al. (2020) reported a significantly higher HR after a simulated fatigue task as compared to baseline HR scores. Additionally, they reported a strong correlation between HR and the corresponding subjective fatigue scores as measured by the Borg scale (Anwer et al., 2020). Since HR has been found to be positively related to subjective fatigue score among high-elevation construction workers (Chang et al., 2009), HR can be used as a surrogate to measure physical fatigue.

While aforementioned studies attempted to directly correlate HR with physical fatigue, some studies tried to categorize HR values at different fatigue levels. Astrand and Rodahl (1986) classified the severity of physical workload based on HR responses (e.g., light work, HR – up to 90 beats/min; moderate work, HR – 90 to 110 beats/min; heavy work, HR – 110 to 130 beats/min; very heavy work, HR – 130 to 150 beats/min; extremely heavy work, HR – 150 to 170 beats/min). Similarly, Adi and Ratnawinanda

(2017) classified fatigue levels according to the percentage cardiovascular load (defined as CVL (%) = (HR_{work}-HR_{rest}) / (HR_{max}-HR_{rest}) x 100) and gave recommendation to workers based on their CVL values. Notably, they classified workers with CVL values less than 30% as no fatigue, while workers with CVL values between 30 and 60%, were recommended to have rest-breaks. For workers with CVL values between 60 and 80% and between 80 and 100%, they are supposed to have a short period of work, and special treatment, respectively. For those with CVL values greater than 100%, they should completely stop working.

Recently, research showed that combining HR with other physiological measures could improve the prediction of fatigue. For example, Umer et al. (2020) predicted 95% of physical fatigue levels using a combination of HR, thermoregulatory, and respiratory metrics in university students during a simulated construction task. However, the accuracy dropped to 57% if only HR data was used to predict fatigue. Similarly, Aryal et al. (2017) reported a 72% prediction accuracy in estimating physical fatigue using combined findings of HR and skin temperature; however, the accuracy dropped to 59% if only HR data was used. These results highlight the benefit of using combined metrics to predict physical fatigue in individuals.

Despite the usefulness of HR for fatigue monitoring, multiple factors (e.g., physical demands, stress and anxiety) can increase HR (Abdelhamid and Everett, 2002; Chan et al., 2012; Gatti et al., 2014). HR can also be influenced by changes in body posture (e.g., sitting to standing) and muscle contraction forces (Astrand and Rodahl, 1986). Therefore, these factors should be considered when HR is intended to be used for fatigue monitoring.

In addition to HR, HRV is a metric of beat-to-beat variation of HR and is found to be a strong marker of cardiac health (Acharya et al. 2004). The measurement of HRV may be an important metric to measure physical fatigue (Achten and Jeukendrup, 2003; Makivic et al., 2013) because a diminished high frequency component of HRV value may indicate heavy physical loads or fatigue in construction workers (Tsai, 2017). A study reported a significant association between workplace stress (physical and mental) and reduced HRV in sedentary and public sector workers (Tonello et al., 2014). Previous construction research has also suggested to monitor both HR and HRV to estimate physical strain in roofers (Lee, 2018; Lee et al., 2017). Nevertheless, previous studies have not directly analyzed the impacts of physical fatigue on HRV parameters. Therefore, future studies should clarify this relationship to determine whether HRV can be used to improve the monitoring of fatigue development during construction activities.

Thermoregulatory metrics

Thermoregulatory measures have also been found to be strongly related to fatigue development during cycling (González-Alonso et al., 1999) and construction tasks (Aryal et al., 2017). Infrared temperature sensors are commonly used to monitor skin temperature and related thermoregulatory changes during fatigue development. Skin temperature is affected by underlying muscular activity, cutaneous blood flow, and sweating patterns at a certain body parts (i.e., cheek, ear, forehead, and temple) (Formenti et al., 2017). During physical exercise, the core body temperature increases, and the body attempts to maintain the core body temperature within a normal physiological limit through thermoregulation. In particular, the skin plays its role by assisting heat transfer from the core body to the atmosphere (Kenney and Johnson, 1992). Five included studies in the current review used skin temperature as a proxy to assess physical fatigue at workplaces among construction workers in different trades including rebar workers, oil and gas industry workers, and manual material handling workers (Chan et al., 2012; Mehta et al., 2017; Aryal et al., 2017; Umer et al., 2020; Anwer et al., 2020). Anwer et al. (2020) reported a significantly increased local skin temperature after 30 minutes of simulated construction task. Similarly, Aryal et al. (2012) reported an increased skin temperature during construction activities. Chan et al.

(2012) reported a rapid increase in the participants' aural temperature in the first 35 minutes of rebar work followed by subsequent slight drop in the core temperature before rising again. These studies show that analyzing the pattern of thermoregulatory changes in perspiration and/or temperature of specific body parts (i.e., cheek, ear, forehead, and temple) have the potential to detect fatigue development.

EMG metrics

Physical fatigue of a local muscle can be detected by analyzing changes in the median frequency or root mean square amplitude of surface EMG signals (Enoka and Duchateau, 2008; Powell and Copping, 2016). Surface EMG has been extensively used to detect muscle fatigue given its noninvasiveness and easy application (Cifrek et al., 2009). By putting two bipolar surface electrodes on a target muscle, the corresponding EMG signals can be measured to estimate the muscle activity. A review highlights that many surface EMG indices (e.g., root mean square of EMG signals, median, and mean power frequencies) can be used to assess muscle fatigue (Cifrek et al., 2009). Specifically, the root mean square amplitude of surface EMG signals in fatigued muscles is significantly higher than that of non-fatigued muscles because fatigue muscles need to activate more muscle fibers to sustain the required force (Dimitrov et al. 2008). Conversely, during muscle contraction, the median frequency and mean power frequency of EMG signals in fatigued muscles are significantly lower than that of non-fatigued muscles (Dingwell et al., 2011; Tenan et al., 2011; Wang et al., 2015).

Previous research has suggested that continuous monitoring of muscle fatigue is feasible by measuring surface EMG activities of the target muscle during various tasks (Cifrek et al., 2009). Four included studies in the current review assessed muscle fatigue using surface EMG metrics (e.g., median frequency and root mean square amplitude) during repetitive tasks among construction workers (e.g., mason) and asymptomatic university students (Anton et al., 2005; McDonald et al., 2016; Calvin et al., 2016; Yin et al., 2019). McDonald et al. (2016) examined the surface EMG activity of shoulder muscles during a simulated upper limb repetitive task. They found statistically significant decreases in median frequency and increased root mean square amplitude of EMG activity immediately following task-related muscle fatigue. Another study revealed significant increase in the average EMG amplitude of fatigued back muscles after a repetitive lifting task (Yin et al., 2019). Similarly, Calvin et al. (2016) detected signs of muscle fatigue (i.e., increased EMG amplitude and decreased median frequency of EMG signals) in the affected shoulder muscles following simulated repetitive work performed at a workstation. The role of EMG in measuring muscle fatigue was further substantiated by Anton et al. (2005). They reported surface EMG amplitudes of various muscles (i.e., lumbar erector spinae, upper trapezius, and forearm flexors and extensors) in bricklayers during the task of laying lightweight concrete blocks (less fatiguing task) was significantly smaller than that during laying standard weight blocks.

Jerk metric

Recent advancement in the wearable sensing technology has provided an opportunity for assessing field-based real-time fatigue (Zhang et al., 2019). Specifically, a typical wearable IMU-based motion capture system, which integrates magnetometers, accelerometers, and gyroscopes to detect velocity, acceleration, and body orientation, is a noninvasive, wireless, and cost-effective technology for measuring body motion during construction tasks (Miller et al., 2004; Yan et al., 2017; Antwi-Afari et al., 2018; Umer et al., 2018b; Yu et al. 2019). Such technology samples kinematic data at a high frequency, enabling the assessments of jerk metrics (the time derivative of acceleration) of the target body parts. Since fatigue may lead to poor motion control and movement quality, increased jerk values during work may hypothetically indicate physical fatigue (Zhang et al., 2019). Jerk metric has been used in clinical research to measure motor control (Zhang et al., 2019). In particular, jerk has been used to: (a) differentiate pathological and non-pathological movements (Hogan and Sternad, 2009;

Balasubramanian et al., 2015); (b) assess motor learning and recovery (Balasubramanian et al., 2011); (c) identify impaired motions (Lapinski, 2013); and (d) assess performance output (Nelson, 1983; Seifert et al., 2014).

Multiple studies have evaluated the feasibility of using the jerk metric to detect and monitor fatigue among healthy adults. Van Dieen et al. (1996) used an optoelectronic system to evaluate the effect of repetitive lifting on joint coordination, loading, and jerk. They revealed that only jerk metric in the lower back and lower extremity joints significantly increased following repetitive lifting. This indicates that jerk metric is sensitive to detect changes in post-fatigue movement patterns, which alters the acceleration, torque and position of body parts. Zhang et al. (2013) used IMUs and machine learning approach to classify normal and post-fatigue walking after a squat exercise. They found that increased acceleration and jerk metric values of lower limbs were associated with the characteristics of post-fatigue gait. Additionally, Maman et al. (2017) used low-noise analogue accelerometers and generalized regression models to detect physical fatigue during simulated manufacturing tasks. They found that features associated with jerk and acceleration at the wrists and hips were better predictors of physical fatigue than features associated with HR. However, only one experimental study has evaluated the feasibility of using jerk metric to monitor physical fatigue among masonry workers (Zhang et al., 2019). The jerk metrics of 11 body parts (i.e., upper arms, forearms, hands, pelvis, thighs, and legs) were measured by wearable IMU sensors. The results showed that the values of jerk metric at the beginning of the task were significantly smaller than the corresponding metrics during a repetitive bricklaying task, indicating physical fatigue (Zhang et al., 2019). Although these results support the idea that the jerk metric can be a potential physiological parameter to measure physical fatigue, further studies that quantify the relationship between jerk metric and physical fatigue are warranted.

Discussion

The discussion section is divided into two subsections namely: wearable sensing technologies for monitoring physiological metrics, and challenges for the application of physiological metrics to assess real-time physical fatigue in construction workers. The first subsection discusses features of different wearable sensing technologies for monitoring physiological metrics. The second subsection includes four sub-subsections: (1) limited validity of physiological metrics for physical fatigue assessments; (2) noise and signal artifacts affecting wearable sensing technology in field measurements; (3) unclear information regarding the cutoff value of each physiological metric for severe physical fatigue; and (4) user acceptance, social and privacy issues in deploying wearable sensing technology.

Wearable sensing technologies for monitoring physiological metrics

A wide range of wearable sensing technologies are available to monitor real-time physiological metrics. However, to obtain a widespread user acceptance in the construction industry, these wearable technologies should be minimally intrusive and fulfil several specific criteria (Dinges and Mallis, 1998). First, the technology should be valid to measure what it is supposed to measure. Second, the technology should provide reliable measurements over time. Third, the technology should have high sensitivity and adequate specificity to detect a true positive case (e.g., physical fatigue) and a true negative case (e.g., no fatigue). Finally, the technology should have the generalization properties so that it can reliably measure the same outcome (e.g., physical fatigue) in the target population.

While some included studies in the current review did not specify a particular construction trade (Abdelhamid and Everett, 2002; Aryal et al., 2017; Hsu et al., 2008; Maiti, 2008; Li et al., 2009), other included studies examined HR in different types of construction workers such as craft workers (Abdelhamid and Everett, 1999), masonry workers (Anton et al., 2005; Das, 2014), road maintenance workers (Roja et al., 2006), carpenters (Bates and Schneider, 2008), manual laborers, high elevation construction workers (Chang et al., 2009), rebar workers (Chan et al., 2012; Wong et al., 2014), roofers (Lee et al., 2017), and cabin field machine operators (Jankovsky et al., 2018). Some studies also examined HR in healthy individuals during simulated construction tasks such as repetitive works and manual material handling task (Anwer et al., 2020; Umer et al., 2020; Yin et al., 2019).

Mobile heart rate monitors are commonly used to monitor HR and HRV during rest or physical activity. These monitors demonstrate very high validity in measuring HR (r = 0.95 to 0.98) (Goodie et al. 2000; Terbizan et al. 2002) and HRV (r = 0.75 to 0.99) (Nunan et al. 2008; Giles et al. 2016; Tsitoglou et al. 2018; Hernando et al. 2018) in healthy individuals. These monitors can assess the functioning of cardiovascular and autonomic systems during and after physical activity. They can be used to monitor real-time physical fatigue and the recovery from fatigue in workers who are involved in physically demanding jobs in the construction industry. There are two types of HR monitors, namely chest straps and optical HR monitors (measuring photoplethysmography (PPG)). Both types of HR monitors are low-cost, commercially available devices to measure real-time HR and HRV during free-living activities. Chest straps include a long elastic band containing a small electrode pad that presses against the skin and a transmitter. The strap is worn around the chest with the electrodes picking up the electrical signals from the heart, which are then transmitted to a transmitter attached in the strap that contains a microprocessor to record and analyze the heart rate. The processed data is then transmitted to a smartphone, a fitness watch, or a computer for real time display or offline analysis. However, this type of device may impede physical activity and is prone to slipping off. Therefore, PPG devices have been developed as an alternative to monitor HR by using light to measure blood flow. A typical PPG device contains a photo detector and several light-emitting diodes of different wavelengths (e.g., red, infrared, and green). The photodetector captures the light refracted off blood flowing through a body part (e.g., wrist, forehead, or ears) to estimate the HR (Allen, 2007). PPG devices are designed to non-invasively collect the volumetric changes of blood flow using low sampling rates (e.g., 64 – 125 Hz) (Ahn et al., 2019). A previous study compared the HRs measured by a PPG device and an electrocardiography (ECG) system in different construction workers including electrician, as well as masonry and dry wall workers (Hwang et al., 2016). They found high validity of using a PPG device to measure HR ($r = 0.85$ to 0.98). Another study also reported high validity of a PPG device (as compared to ECG-based device) in measuring HRV in healthy individuals ($r = 0.83$ to 0.95) (Arberet et al., 2013). Since

PPG devices only use a single sensor and the location of sensor placement is very convenient (e.g., wrist), they are suitable for HR monitoring. Various physiological metrics (e.g., HR, HRV, skin temperature) can also be extracted from PPG signals to assess physical fatigue in construction workers. However, since PPG sensors do not measure cardiac activity directly, there is a delay in measuring cardiac activity using PPG (Lu et al., 2009). Furthermore, PPG signals can be significantly affected by multiple factors such as biological factors (blood content), sensing factors (sensor geometry) and cardiovascular factors (e.g., arterial blood volume) (Lemay et al., 2014), as well as motion artifacts (Mashhadi et al., 2015). Therefore, headband- or ear-type PPG devices may be used to replace wristband-type PPG devices to monitor HR during tasks that involve a lot of wrist movement. Researchers have also used noise-cancellation algorithms based on HR data obtained from daily activities (e.g., running) in a well-controlled laboratory to improve the accuracy of PPG-based HR monitoring (Parak et al., 2014; Tamura et al., 2014; Zhang et al., 2015). Additionally, many PPG devices have built-in data pre-processing algorithms to improve the accuracy of HR monitoring during various intensive physical activities (Tamura et al., 2014). However, further studies are warranted to examine the validity of using these methods to continuously monitor cardiovascular functioning in construction workers whose tasks may involve excessive motion artifacts and high physical demands.

Additionally, some assessment tools (e.g., Zephyr Bioharness™ and Equivital EQ02 LifeMonitor) use several wearable sensors together to assess biomechanical (e.g., acceleration) and physiological (e.g., skin temperature, HR, HRV, and breathing rate) data during work tasks. However, only a few studies have evaluated the reliability and validity of using these technologies in construction workers. The Zephyr Bioharness™ is the most popular wearable sensor originally designed to optimize the performance of professional athletes by continuously monitoring several physiological data to track functional movements and workload (Pantelopoulos and Bourbakis, 2009; Li et al., 2016). Bioharness™ is moderately reliable in measuring skin temperature (ICC = 0.61) (Johnstone et al. 2012b). Some studies reported excellent reliability of using this device to measure HR (ICC = 0.92 to 0.98) (Kim et al. 2013; Dolezal et al. 2014; Rawstorn et al. 2015; Nazari et al. 2017) and breathing rate (ICC = 0.90) (Hailstone and Kilding, 2011). Conversely, Johnstone et al. (2012a) found good to excellent validity of using Bioharness™ to measure HR but the breathing rate data showed more variability during a walk-jog-run test protocol in healthy individuals. Similarly, the test-retest reliability of the device showed excellent reliability for HR monitoring (intraclass correlation coefficient, ICC = 0.91), whereas the breathing rate data showed fair reliability (ICC = 0.46). The low reliability of Bioharness™ in measuring breathing rate may be attributed to the higher variability in the breathing rate during high velocity activities (Johnstone et al. 2012a). Lee et al. (2017) used Bioharness™ to measure HR and HRV in roofers and found that HR and HRV data collected from roofers in a single day was not sufficient to monitor the physical demands of these workers. They recommended using the average HR in two days and average HRV in four days to better reflect the typical workload of these workers at works. Collectively, Bioharness™ may have the potential to monitor the real-time physiological status of construction workers but further validation is needed before using it to modify workers' work intensity or to avoid physical fatigue and fatigue related workplace accidents.

Likewise, the Equivital (EQ02) is marketed as a safe, wearable vest embedded with textile-based electrodes to monitor real-time cardiorespiratory (e.g., HR, HRV, breathing rate) and thermoregulatory (e.g., skin temperature) parameters. A previous study compared the reliability and validity of using the EQ02 to measure HR, breathing rate, and skin temperature during physical activities of different intensities (e.g., rest, low- and moderate intensities) in healthy individuals with reference to respective standard measurement devices (Liu et al. 2013). The EQ02 demonstrated excellent reliability and validity in measuring HR (ICC = 0.99; r = 0.98), breathing rate (ICC = 0.96; r = 0.97), and skin temperature (ICC = 0.97; r = 0.96). Compared to the measurements of standard devices, the EQ02 only showed small mean differences in the HR (1.2 beats/minute), breathing rate (0.2 rate/minute), and skin temperature (0.59 ℃) during all tasks. Similarly, the EQ02 found very small mean differences in two repeatedly measured HRs (-0.8 beats/minute), breathing rates (-0.2 rate/minute), and skin temperatures (0.25 ℃), indicating good test-retest reliability of the device. Additionally, Akintola et al. (2016) compared the EQ02 with a Holter device for continuous monitoring of HR and HRV in healthy individuals at home. They demonstrated that the HR and HRV data measured by the EQ02 were highly correlated with those measured by the Holter device (r = 0.99 and 0.78, respectively) when the component of motion artifacts was small (20% or lower artifacts). The relative mean absolute difference in HR between the EQ02 and the Holter device was small (1.5%) when the motion artifacts was <20%. Interestingly, they found least active people (based on the step counts taken during the study period) showed significantly lower motion artifacts percentage (73.3% of the data had <20% artifacts) as compared to moderately and highly active individuals (66.2% of the data had <20% artifacts). Since the accuracy and precision of the EQ02 is highly affected by movement artifacts, the

EQ02 may be inappropriate for monitoring workers' physiological status during construction activities because they involve a lot of body movements.

Surface EMG is an easy, convenient, and reliable technology to assess local muscle fatigue (Dedering et al., 2000; Koumantakis et al., 2001; Ali et al., 2001; Arnall et al., 2002; Farina et al., 2003). The test-retest reliability of surface EMG in measuring muscle fatigue ranged from 0.51 to 0.97 (intraclass correlation coefficients) (Dedering et al. 2000; Koumantakis et al. 2001; Ali et al., 2001; Arnall et al. 2002). EMG sensors comprise bipolar surface electrodes attached to specific muscle masses to capture the myoelectrical activity of target muscles. The EMG signals often produce two standardized EMG metrics namely time-domain metrics (e.g., mean absolute value, compression normalization, root-mean-square normalization) (Anton et al., 2001; Trask et al., 2007, 2010) and frequency domain metrics (e.g., mean frequency, median frequency, and power spectrum density) (Jebelli and Lee, 2019). Previous studies have attached EMG sensors to workers' different body parts (neck, shoulders, forearm, back) during masonry tasks (Anton et al., 2005), lifting activities (Anton et al., 2005; Nimbarte et al., 2010), or overhead activities (Anton et al., 2001; Jia et al., 2011) to measure muscle fatigue. Although surface EMG measurements appear to suit the non-invasive monitoring of muscle fatigue during construction tasks, surface electrodes should be attached to the target muscle, which may interfere with construction workers' work. Furthermore, EMG signals can be easily compromised by the quality of skin preparation, sweating, ambient temperature, and movement artifacts. Therefore, its application in the field is limited and needs further research/refinement.

An IMU-based motion capture system is a noninvasive, wireless, and effective technology designed to measure body motion and jerk during movement. This system comprises 17 IMU sensors, each includes a three-axis magnetometer, three-axis accelerometer, and three-axis gyroscopes to detect velocity, acceleration, and body orientation. They can provide a high-frequency sampling rate to assess a jerk metric. Akin to surface EMG measurements, motion sensors need to be attached or put onto the target body parts to measure body kinematics. However, commercially available sensors are quite expensive, and the wearing of such sensors may interfere with construction workers' performance. Therefore, lighter and more affordable sensors are needed to assess jerk metrics and physical fatigue in the field. Additionally, the reliability and validity of IMU for jerk measurement have not been reported. Future studies should examine the reliability and validity of the jerk metrics in assessing physical fatigue during certain construction tasks.

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Challenges for the applications of physiological metrics for real-time physical fatigue assessment during construction tasks

Although various physiological metrics (such as HR, HRV, skin temperature, EMG, and jerk metrics) may be used to estimate physical fatigue during construction tasks, there are some challenges in using wearable sensing technologies to monitor physiological metrics for the real-time physical fatigue assessments.

Limited validity of physiological metrics for physical fatigue assessments

While preliminary results of applying physiological metrics to assess physical fatigue are promising, only limited studies have directly examined the relationship between changes in physiological metrics and physical fatigue in construction workers. To the best of our knowledge, no study has evaluated the use of physiological sensors in assessing fatigue in a large sample of construction workers over a prolonged period (e.g., a few days or weeks). Furthermore, no study has validated the use of physiological metrics against the gold standard physical fatigue assessment (i.e., blood lactate level). That said, a few studies have suggested that the combined physiological metrics can predict fatigue level with a higher accuracy as compared to a single metric. Additionally, certain physiological metrics (e.g., HR, HRV, skin temperature) have the face validity to evaluate generalized physical fatigue, while others (e.g., EMG and jerk metrics) are more suitable to assess localized muscle fatigue.

Noise and signal artifacts affecting wearable sensing technology in field measurements

While physiological metrics are better than the traditional questionnaire approach to monitor physical fatigue without impeding workers' ongoing activities, it is challenging to apply wearable sensing technologies to monitor physiological metrics at construction sites. The accuracy and function of the wearable sensing technology in monitoring physiological metrics can be influenced by multiple factors (Jebelli et al., 2018a; Ahn et al., 2019). Any undesirable signals or signals that obstruct the target signals are known as signal artifacts (De Luca et al., 2010). There are two types of physiological signal artifacts: intrinsic and extrinsic, and both may interfere with the target signals (Ahn et al., 2019). While intrinsic signal artifacts are originated from the body, such as respiration, pulse, skin, motion, muscles, and ocular artifacts, extrinsic signal artifacts are usually generated from external sources such as environmental noise and workers' movements (Ahn et al., 2019), motion artifacts, device power–line interference, electrode movement artifacts, and sensor deployment and placement (Jebelli et al., 2018a). Unlike collecting physiological metrics in a well-controlled laboratory setting with minimal environmental noise, data collection of these metrics at construction sites needs to face frequent workers' movements and the ever-changing construction environment. Therefore, wearable sensing technology in construction sites should be refined to improve the data collection of physiological metrics for physical fatigue assessments.

Since both extrinsic and intrinsic signal artifacts may conceal desirable signals, it is recommended to remove or reduce those signal artifacts before signal processing (Ahn et al., 2019). Many filtering methods have been developed to minimize these signal artifacts (Iriarte et al., 2003; Manoilov, 2006; Ram et al., 2012; Daly et al., 2013). For instance, previous research used a wavelength shrinkage method to minimize the mixed noise recorded from the wearable sensing device (Kang et al., 2017). Similarly, Gibbs and Asada (2005) developed an active noise cancellation method to minimize signal artifacts originated from body movement during data collection using a wearable PPG sensing technology. However, these techniques may be inadequate to apply in construction sites due to the significantly higher signal artifacts in the field.

Accordingly, signal processing methods are suggested to eliminate both extrinsic and intrinsic signal artifacts recorded from wearable sensors in construction sites (Jebelli et al., 2018b). Jebelli et al. (2018b) used filtering methods (including band-pass filter, low-pass filter, and notch filter) to reduce the signal artifacts obtained from external sources (e.g., body movement, electrode movement artifacts, etc.). They also used an independent component analysis method to identify and minimize internal signal artifacts (e.g., vertical eye movement, eye blinking, and muscular movement) during recording with PPG wristband-type sensing technology. Although the results of these methods are promising, future studies should evaluate the quality and type of signals obtained from wearable sensing technology under various conditions at the construction sites so as to understand various forms or sources of artifacts, and to remove and minimize these noises from the captured signals (Ahn et al., 2019).

Lack of information regarding the cutoff value of each physiological metric for severe physical fatigue

Another major challenge of applying physiological metrics to assess physical fatigue during construction tasks is the lack of information regarding the cutoff value of each physiological metric for severe physical fatigue. While it is thought that people experience physical fatigue for a prolonged period may cause specific physical symptoms and increases the risk of musculoskeletal disorders and work-related injuries, little is known regarding the cutoff values for various physiological signals to indicate extreme fatigue. This is one of the most important challenges when analyzing the outcomes of physiological metrics obtained from the wearable sensing technology because each individual has specific fatigue response when doing different tasks in different environments. Therefore, it is important to determine the task-specific cutoff value for each physiological metric value in individual, above which would indicate severe unsafe fatigue.

User acceptance, social and privacy issues in deploying wearable sensing technology

User acceptance in wearing these sensors in terms of comfort level, privacy issues, expected effort for don and doff, usefulness, and willingness to use have become important considerations when applying and deploying wearable sensing technologies at construction sites. A previous study indicated that only about 10% of construction workers were using wearable sensing technology, although more than 90% of workers used smartphones (Zack, 2016). Various models of technology acceptance, such as the use of technology and unified theory of acceptance (Venkatesh et al., 2003), and the technology acceptance model (Davis et al., 1989) have been proposed and examined in different fields. Based on these models, various practical models such as web-based training (Park et al., 2012), project management information system (Lee and Yu, 2012), building information modeling (Son et al., 2015; Zhang et al., 2013), and mobile computing (Son et al., 2012) have been developed by construction researchers to assess factors affecting the acceptance of technology by users. Future studies should adapt these models to evaluate the best approach to improve the acceptance of using wearable sensors to measure physical fatigue in construction workers.

Another pragmatic issue that can affect the uptake of wearable technology for fatigue monitoring in the construction field is data security. In order to protect the health-related information collected from wearable sensors, all communication between sensors and servers should be encrypted to prevent the loss of user's privacy and data (Jovanov et al., 2005). Since wearable sensing technologies are susceptible to data breaching and security risk, robust security measures should be in place to protect against cyberattacks that can destroy or steal personal data (Awolusi et al., 2018). In short, the wearable sensing technology should be minimally invasive, and equipped with the highest possible security and safety for construction industrial use (Cheng et al., 2011).

Future research directions

While the included studies have shown that different physiological metrics (i.e., HR, HRV, skin temperature, EMG activity, and jerk metrics) have the potential to objectively detect physical fatigue during construction tasks, further research is warranted to improve the application and development of wearable sensing technology to measure physiological metrics for real-time physical fatigue monitoring in construction workers. The following sections discuss various potential future research directions.

Reliability and validity of wearable sensing technologies for collecting physiological metrics in construction workers

Previous studies only investigated the reliability and validity of using wearable sensing technologies to monitor physiological metrics for physical fatigue assessments in a small number of participants in laboratories. They failed to validate the fatigue findings obtained from wearable sensing technologies with the gold standard method (blood lactate concentration). Future field research should compare physical fatigue results as measured by wearable sensing technology with the corresponding blood lactate concentration. Additionally, further research is warranted to quantify the associations between changes in these physiological metrics and corresponding changes in fatigue levels during various construction tasks. Since many of these physiological parameters can be affected by multiple factors (e.g., surrounding temperature, weight, age), future research should derive relevant fatigue prediction models for each parameter after considering different potential confounding variables. Specifically, different cutoff values for each physiological metric should be determined to help distinguish different physical fatigue levels. For example, the maximum acceptable value of each physiological metric should be determined in order to ensure workers work safely without fatigue for each construction activity. Given inter-individual variations in physiological responses to tasks, people may show different physiological metric values for the same level of perceived exertion. For example, Umer et al. (2020) found that for a perceived exertion level of 14 out of 20 (measured by Borg RPE 20-scale), participants' heart rates ranged from 87 to 132 beats per minute. The authors hypothesized that biochemical markers for fatigue (e.g., blood lactate levels) might be very closely related to the threshold values of certain psychometric metrics although this hypothesis should be tested in future research.

Integration of two or more wearable sensing technologies

The applications of wearable sensing technologies in real construction environments are often affected by noise and signal artifacts. While many filtering methods have been proposed to minimize these signal artifacts, combining information from two or more technologies would negate the impacts of signal noise, and improve the accuracy of fatigue measurements. Fusion of sensors has already been practiced in medical research to eliminate motion-related signal artifacts in physiological data recorded by wearable sensing technology (Ahn et al., 2019). Specifically, IMUs sensors were used to measure physical movements to negate movement-related signal artifacts in physiological sensor data. A previous study used IMU data to adjust for signal artifacts originated from gait-related body movements in EEG analyses (Kline et al. 2015). The same principle can be applied to wearable sensor technologies to eliminate movement artifacts collected from physiological sensors. Future studies can determine the signal-to-artifacts/noise ratio as well as artifacts/noise spectrums in different physiological metrics during various construction tasks so as to refine the estimation of task-specific physical fatigue.

Development of personalized wearable warning-based technologies for mitigating workers' physical fatigue

Previous studies have suggested that the application of warning-based sensing technologies can minimize the risk of fatal and nonfatal occupational accidents at construction sites (Heng et al., 2016; Yi et al., 2016). Yi et al. (2016) designed a mobile communication warning-based system using environmental sensors to warn workers at risk of heat stress during hot and humid environments. Similar future studies should develop a personalized wearable warning-based technology to monitor real-time fatigue levels using automatically collected physiological metrics. This technology may also be used by construction site managers to monitor workers who are at risk of excessive physical fatigue or recovering from physical fatigue at work.

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Evaluation of user acceptance and privacy issues of using wearable sensing technologies for collecting physiological metrics

User acceptance and privacy issues affect the adoption of wearable sensing technology for monitoring physical fatigue-related physiological metrics. Recently, Choi et al. (2017) reported that privacy issues, usefulness, and social impact are the commonest factors affecting construction workers' acceptance of smart vest and wristband based wearable sensing technologies. Although this study provided some theoretical frameworks regarding the acceptance of wearable sensing technology in the construction industry, the relationship between various features of wearable sensing technology (e.g., design and function), context of use (e.g., monitoring) and impacts on user acceptance remains unknown. Future studies should evaluate the best method to promote usage of wearable sensing technology for fatigue monitoring in construction workers. Specific scales (e.g., a visual analogue scale) can be developed to assess user acceptance of using the wearble sensing technologies based on their comfort level, social and privacy issues, perceived efforts for don and doff, and perceived usefullness.

Conclusions

The current review summarized the state-of-the-art of physiological metrics for the real-time measurement of construction workers' physical fatigue. This review used systematic search methods to solicit relevant data, and to critically appraise the application of physiological metrics in measuring physical fatigue in construction workers. Several physiological metrics have the potential for real-time measurement of physical fatigue in construction workers. While the HR metric is the most commonly used physiological metric to measure fatigue during construction works, other physiological metrics (skin temperature, EMG, HRV, and jerk metrics) can also evaluate fatigue. The current review highlights that using multiple physiological metrics are more accurate than using a single metric in monitoring physical fatigue during construction tasks. Various wearable sensing technologies have been developed to measure these physiological metrics, but many technical challenges (e.g., limited validity, noise and signal artifacts, lack of cutoff value for fatigue, user acceptance, and social and privacy issues) remain to be overcome before these physiological metrics can be adopted to assess real-time physical fatigue. As such, it is important to compare the fatigue findings measured by wearable sensing technologies with that by the gold standard blood test to refine the fatigue prediction. Since multiple intrinsic and extrinsic artifacts may lower the accuracy of wearable sensing technologies in assessing real-time fatigue, it is paramount to improve the data processing approach in order to minimize errors. Future studies should also quantify the signal-to-artifacts/noise ratio, as well as artifacts/noise spectrums in different physiological metrics during various construction tasks so as to refine the estimation of task-specific physical fatigue. Collectively, a better real-time detection of construction workers' physical fatigue can help design appropriate personalized work-rest schedules, or proper work task adaptations to mitigate their health hazards and optimize their productivity and work quality.

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Figure Legend

Fig 1. Study selection process and results of the literature search

Fig 2. Number of citations for each physiological measure (HR, Heart rate; HRV, Heart rate variability; ST, Skin temperature; EMG, Electromyography)

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Table 1: Search strategy

Keywords (25-07-2020)	**Web of Science**	**PubMed**	**Medline**	**CINAHL Complete**	**EMBASE**
Fatigue OR Exertion OR Tiredness OR physical effort OR muscle fatigue OR Physical fatigue	275,734	173800	167,660	49,576	586,726
Heart rate OR heart rate variability OR thermoregulation OR skin temperature OR electrocardiogram OR respiration frequency OR breathing frequency OR core body temperature OR electromyography OR muscle activity OR Jerk OR physiological measures	399,341	707351	449,290	75,300	1,293,271
Construction workers OR Construction industry OR Construction trade OR Construction sector OR Industrial Construction OR Construction	647,715	133672	136,655	39,324	143,199
Combined	72	60	56	22	114
Total after duplication removed			164		

Table 2: Characteristics and findings of included studies

Authors	Country	Study design	Sample size	Participants	Physical tasks	Physiological metrics (Objective fatigue measures)	Subjective fatigue assessment	Instrumentation used	Results	Conclusions
Abdelhamid and Everett, 1999	USA	Cross-sectional study Laboratory study (task simulation)	N = 8 Age: Mean 30.7 ±5.39 years	Construction craft workers	Concrete slab placing and finishing work	HR (bpm)	Questionnaire	POLAR Vantage XL heart rate monitor (Polar Electro Oy, Kempele, Finland)	An increase in HR was followed by an increase in VO_2 during works. Similarly, a decrease in HR was followed by decrease in VO_2 during rest period.	Most of the workers experienced physical fatigue during tasks as reflected by increased HR.
Abdelhamid and Everett, 2002	USA	Cross-sectional study Field study	N = 100 Age: Average	Construction workers (12 trades)	Multiple construction tasks	HR (bpm)	Questionnaire	POLAR Vantage XL heart rate monitor (Polar Electro Oy, Kempele,	Mean HR values indicated that about 45% of construction workers were	20 to 40% of craft workers routinely worked at a level exceed the thresholds of

			36.7 years					Finland)	performing heavy to extremely heavy work. Peak HR values indicated that about 63% of construction workers were performing heavy to extremely heavy work.	physiological loads for manual work as measured by HR. These workers were vulnerable for physical fatigue.
Anton et al., 2005	USA	Cross-sectional study Laboratory study (task simulation)	N = 21 Age: Mean 33.5 ±10.4 years	Apprentice-level, Masonry workers Mean age = 33.5 Years	Construction of concrete block walls	HR (bpm) Surface EMG (Root mean square amplitude)	None	Polar S720i heart rate monitors Surface EMG (EMG-67, Therapeutics Unlimited, Iowa City, IA, USA)	The mean maximum HR was 117 (SD 11.5) bpm for light-weight concrete blocks and 119 (SD 12.3) bpm for standard-weight blocks (p =	Laying of light-weight concrete blocks caused lower EMG amplitudes compared to standard-weight blocks. However, there were no significant

									0.58). A significant difference in the changes of EMG activity was noted while laying of light-weight concrete blocks and standard-weight blocks (p = 0.01).	differences in HR noted between laying the two types of blocks.
Roja et al., 2006	Latvia	Cross-sectional study Field study	N = 20 Age: Mean 35 ± 4 years	Road maintenance workers	sand layer construction cycle chipping layer construction cycle asphalt layer	HR (bpm)	Borg scale (6 – 20)	Polar S810 Heart Rate Monitor (Polar Electro Inc., Woodbury, NY, USA)	Fatigue in workers as indicated by increased HR during road construction and repairing works.	This study concluded that a complex ergonomic analysis comprising of HR monitoring is adequate to evaluate work fatigue during

					construction cycle					these construction tasks.
Bates and Schneider, 2008	UAE	Longitudinal observational study Field study	N = 22 Age: not reported	Carpenters steel fixers general laborers	construction of a large concrete water feature	HR (bpm) Aural temperature (degree centigrade)	None	Polar S720i heart rate monitors Tympanic thermometers	Changes in HR was statistically non-significant during 3 days of construction works. Aural temperature of the workers was remained unchanged during 3 days of construction works.	Since construction tasks did not cause any adverse physiological effects, workers did not have fatigue to show significant changes in HR or body temperature.
Hsu et al., 2008	Taiwan	Longitudinal observational study Field	N = 80 Age: Mean 39.3 ±	Construction workers	Construction of high-rise building	HR (bpm)	Research Committee on Industrial Fatigue scale	Wrist blood pressure meter (Terumo, Model ES-P2000, Japan)	Worker's HR increased by 9 to 14% after construction work.	High-rise building construction work is physically demanding. Workers are prone to develop fatigue

		study	12.02 years							as indicated by increased HR during construction tasks.
Maiti, 2008	India	Observational study Field study	N = 20 Age: 28 – 32 years	Construction workers	Multiple manual tasks	HR (bpm)	None	Pacer heart rate monitor (Polar Sport Tester TM, Polar Electro Oy, Finland)	Average working HR of workers were 124.1 bpm. The working HR was significantly correlated with the resting time.	Higher workload as measured by HR in building construction industry may cause unsafe working condition for construction workers.
Chang et al., 2009	Taiwan	Cross-sectional study Field study	N = 302 Age: Mean 38.2 ± 8.9 years	High-elevation construction workers	Construction of high-rise building	HR (bpm)	Questionnaire	Polar Vantage NV Heart rate monitor (Sark Production, MA)	The baseline HR of the workers were not associated with the occupations and the average HR in each occupation	The extent of fatigue varies among different occupations of construction workers as indicated by HR.

									ranged between 73 and 77 bpm. The average changes in HR was 112.4 bpm for all workers.	
Li et al., 2009	Taiwan	Experimental study Laboratory study	N = 8 Age: Mean 25.3 ± 4.3 years	Construction workers	Box handling task	HR (bpm)	Borg scale (6 – 20)	POLAR Vantage XL heart rate monitor (Polar Electro Oy, Kempele, Finland)	The average HR was higher during tasks performed at the frequency of twice per minute than that of once per minute (111.3 vs 97.0 bpm). HR (r=0.49) was associated with physical fatigue as measured by RPE.	Both frequency and height variables of construction tasks significantly impact worker's physiological response on whole body fatigue as indicated by increased HR during box handling task.
Chan et al.,	Hong	Experimen	N =	Rebar	fixing	HR (bpm)	Borg CR10	POLAR Vantage	The resting HR	Fatigue was

2012	Kong	tal study Field study	19 Age: Mean 45 ± 8.3 years	workers	and bending steel reinforcement bars	Temperature (degree centigrade)	Scale	XL heart rate monitor (Polar Electro Oy, Kempele, Finland) Infrared tympanic electronic thermometer (Genius TM2, COVIDIEN, USA)	was decreased slightly at the beginning and remained stable. The HR increased gradually at the time of rebar work. The average HR of the participants increased by 40 bpm. Core temperature was rapidly increased at the beginning of 35 minutes of rebar works. After 35 minutes of rebar, core temperature of most	accompanied by increased HR during rebar work. Additionally, rapid increase of core temperature was seen at the beginning of fatigue and then temperature was reduced and maintained at a stable condition.

									participants was decreased and remained stable.	
Das, 2014	India	Cross-sectional study Field study	N = 220 Age: Mean 33.5 ±6.2 years	Construction workers	brick field works	HR (bpm)	None	Manual	The participants HR rose to > 100 bpm. The average HR of brick field workers was 148.6 bpm after the construction tasks.	Brick field workers had severe physiological stress as indicated by increased HR.
Wong et al., 2014	Hong Kong	Experimental study Field study	N = 39 Age: Mean 42.2 ±10.9 years	Rebar workers	Bar bending and bar fixing task	HR (bpm)	Borg CR10 Scale	POLAR heart rate monitor (Polar Electro Oy, Kempele, Finland)	Bar fixing task induced significantly higher HR (113.6 vs. 102.3 bpm), than bar bending task.	HR metric can be used to assess physical fatigue during rebar working.
McDonald et al., 2016	Canada	Cross-sectional study	N = 12 Age:	University students	Simulated repetitive	Surface EMG (Root	Borg scale (6 – 20)	Surface EMG (Trigno, Delsys Inc., Natick, MA,	Surface EMG signals revealed decrease median	Participants showed sign of muscle fatigue as

		Laboratory study (task simulation)	20–24 years		work	mean square amplitude and median frequency)		USA)	frequency and increase root mean square amplitude following repetitive work.	indicated by decrease median frequency and increase root mean square amplitude signal of surface EMG during work.
Calvin et al., 2016	Canada	Cross-sectional study Laboratory study (task simulation)	N = 12 Age: 20–24 years	University students	Simulated repetitive work	Surface EMG (Root mean square amplitude and median frequency)	Borg CR-10 scale	Surface EMG (Trigno, Delsys Inc., Natick, MA, USA)	Signs of muscle fatigue (i.e. increased EMG amplitude, decreased EMG frequency) in anterior deltoid muscle following simulated repetitive work (pulling, pushing, and drilling works)	Although the results of this study identified muscle fatigue due to repetitive works, participants were able to complete post-fatigue tasks by adaptation of muscle recruitment.

									were noted in the affected muscles.	
Aryal et al., 2017	USA	Experimental study Laboratory study	N = 12 Age: Mean 43.8 ±15.2 years	Construction workers	Simulated material handling task	HR (bpm) Skin temperature (degree centigrade)	Borg's RPE scale (6 – 20)	Wrist band (Garmin vivofit) Non-contact infrared temperature sensors (MLX90614)	An increase in the HR during simulated material handling task, and reduced HR during rest time. Skin temperature increased during physical activity.	Physical fatigue can be identified by assessing physiological measures including HR and skin temperature.
Lee et al., 2017	USA	Reliability study Field study	N = 6 Age: Mean 33.5 ±7.12 years	Construction workers	Roofing activities	HR (bpm) HRV (milliseconds) Energy expenditure (kcal/min)	Questionnaire	Zephyr BioharnessTM sensors (Medtrionic, Dublin, Ireland) ActiGraph GT9X unit (ActiGraph, LLC., Pensacola,	Significant differences in HR, HRV, and energy expenditure were noted during construction	Participants showed significantly increased HR, HRV, and energy expenditure during 5 days of roofing works.

								Florida)	activities.	
Mehta et al., 2017	USA	Observational study Field study	N = 10 Age: Mean 31.3 ± 6.1 years	Oil and gas extraction (OGE) industry workers	offshore shiftwork	HR (bpm) Skin temperature (degree centigrade)	The Swedish Occupation Fatigue Inventory (SOFI)	EQ02 LifeMonitor, Equivital™, Cambridge, UK	Average HR increased for all workers and remained high at the end of works.	Physiological measures highlighted the negative effects of shiftwork on HR responses. However, lack of correlation was noted between subjective fatigue perceptions and physiological responses.
Tsai, 2017	Taiwan	Experimental study Field study	N = 20 Age: 25 -32 years	Construction workers	Multiple construction tasks	HRV (milliseconds)	Perceived fatigue	Photo Plethysmography-based wearable device (Garmin, 2016)	Physiological status monitoring of workers using HRV identified more fatigue risk than manual inspection.	Assessment of HRV is a useful approach to evaluate real-time fatigue during construction tasks.

Jankovský et al., 2018	Czech Republic	Observational study Field study	N = 5 Age: Mean 42.8 ±8.8 years	Cabin field machines operators	Operating field machine	HR (bpm)	None	Biofeedback 2000 x-pert device	The average working HR of the machine operators was 91 bpm, and their resting HR was 66 bpm. The average HR of the operators was 90 bpm at the beginning of the shift, while it was 86 bpm in the middle of the shift, and it was 100 bpm at the end of the shift.	The elevated HR during operating filed machine depends on various factors including type of machine, part of shift (middle), and height and weight of operators.
Yin et al., 2019	China	Experimental study Laboratory study	N = 12 Age:	Healthy individuals	repetitive lifting task	HR (bpm) Surface EMG (Root	Borg's RPE 6–20 scale	Digital heart rate monitor (PC-80D, China) Surface EMG	The average post-testing HR was higher than that of pre-	Increased HR and EMG amplitude of erector spinae muscle suggests

			Mean 26.4 ± 5.1 years			mean square amplitude and median frequency)		(ME6000-8, Bittium Inc., Kuopio, Finland)	testing HR. Post-testing EMG amplitude of erector spinae muscle was higher than the pre-testing value.	physical fatigue during repetitive lifting task.
Zhang et al., 2019	Canada	Experimental pilot study Laboratory study	N = 32 Age: Mean 26.7 ± 3.1 years	Masonry workers	Bricklaying task	Jerk metric (g/sec - time-derivative of the acceleration magnitude)	None	A wearable IMU-based motion capture suit, Noitom Perception Neuron	Differences of jerk metric could be used to differentiate fatigue and non-fatigue states.	Jerk is an indicator of physical fatigue during a bricklaying task.
Anwer et al., 2020	Hong Kong	Experimental study Laboratory study	N = 25 Age: 31.8	Healthy individuals	Simulated manual material handling	HR (bpm) Skin temperature (degree	Borg's RPE 6–20 scale	EQ02 LifeMonitor, Equivital™, Cambridge, UK	Mean HR was increased from 70.2 BPM at baseline to	The results of this study suggest the use of HR and skin temperature

		± 1.8 years	task	centigrade)		120.2 BPM after 30 minutes of simulated fatigue task. Local skin temperature was increased from 31.5℃ at baseline to 34.9 ℃ after 30 minutes of simulated fatigue task. There were significant correlations found between HR or skin temperature and the corresponding Borg scores at the end of	to assess physical fatigue during a simulated construction task.

									simulated fatigue task.	
Umer et al., 2020	Hong Kong	Experimental study Laboratory study	N = 10 Age: Mean 27.5 ±2.76 years	Healthy individuals	Simulated manual material handling task	HR (bpm) Skin temperature (degree centigrade)	Borg's RPE scale (6 – 20)	EQ02 LifeMonitor, Equivital™, Cambridge, UK	Combined HR and skin temperature metrics can predict fatigue levels with a higher accuracy (95%). However, the accuracy dropped to 57% for individual metric for fatigue prediction.	This study concluded the advantage of using multiple physiological metrics to measure physical fatigue in construction workers.

HR: Heart rate; bpm: beat-per-minute; HRV: Heart rate variability; SD; Standard deviation; EMG: Electromyography; RPE: Rating of perceived exertion; N: Number

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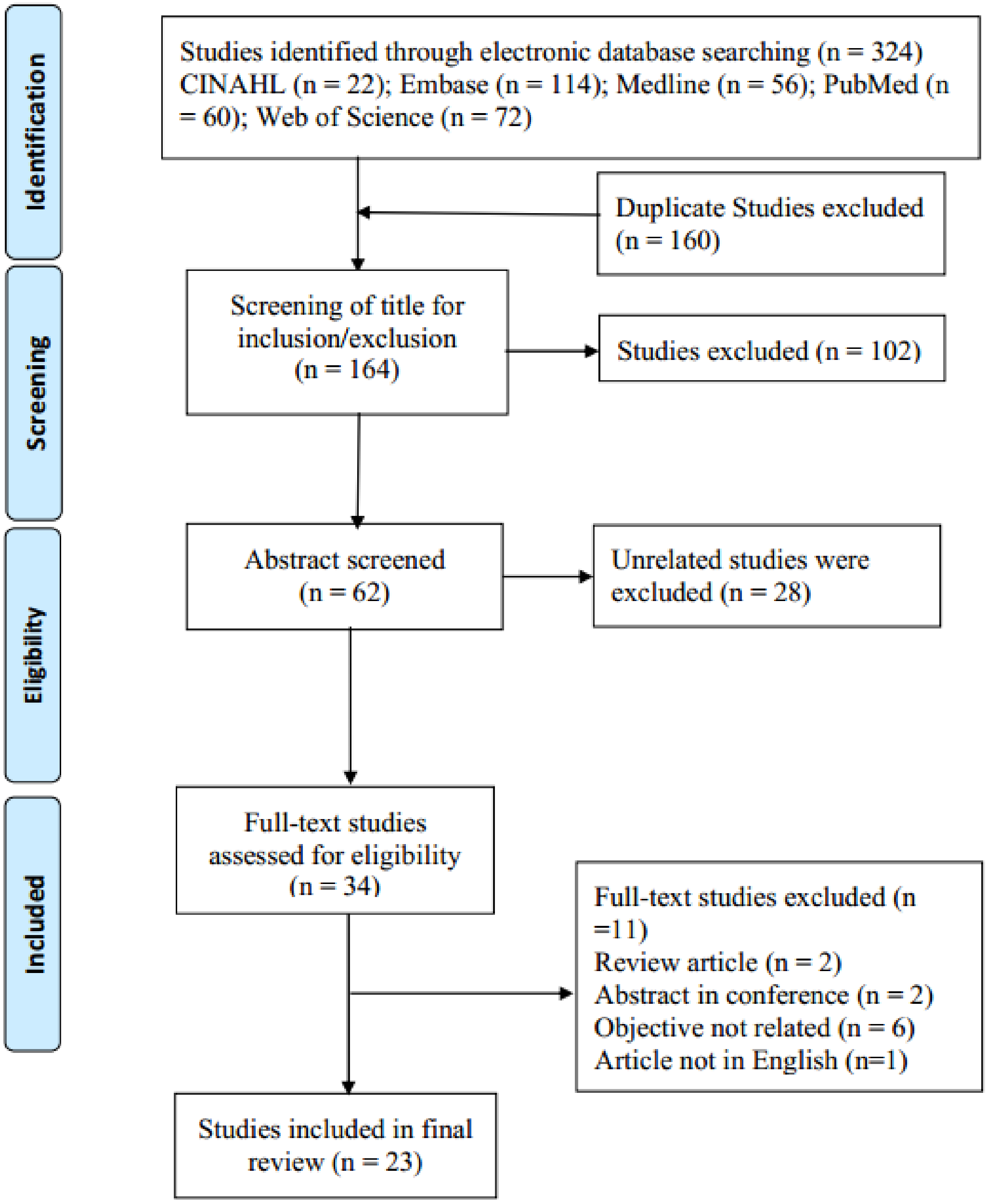

Fig. 1. Study selection process and results of the literature search.

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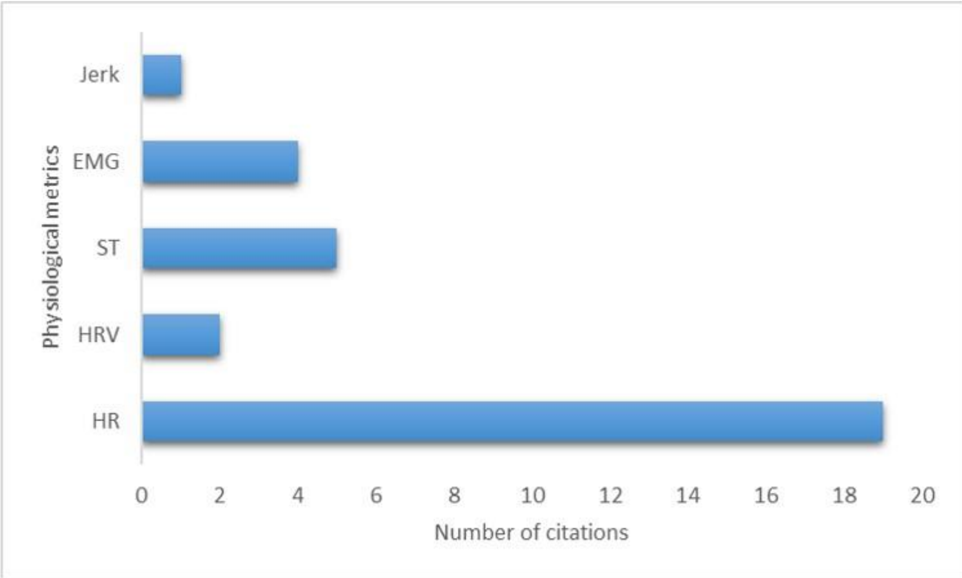

Fig. 2. Number of citations for each physiological measure (HR = heart rate, HRV = heart-rate variability, ST= skin temperature, and EMG = electromyography)