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SUB-ACTIVITY ANALYSIS BY USING WRISTBAND-TYPE WEARABLE HEALTH DEVICES TO MEASURE CONSTRUCTION WORKERS' PHYSICAL DEMANDS

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Abstract. Understanding and managing the physical demands of construction workers is critical to their safety, health, and productivity. Construction tasks, especially cyclic and non-cyclic activities are highly variable. Cyclic tasks involve repetitive actions, which if not well-distributed, can lead to cumulative fatigue and long-term health issues. Conversely, non-cyclic tasks are unpredictable and irregular, making it challenging to allocate workloads effectively. Despite these challenges, few studies have investigated continuous physical demands for both task types, particularly in dynamic, on-site construction environments. Filling this gap is essential for developing practical strategies to improve workload allocation, mitigate health risks, and optimize workforce management. This study addresses this critical gap by using lightweight wearable wristbands equipped with heart rate (HR) biosensors to monitor workers' activities without disrupting their tasks. The percentage of heart rate reserve (%HRR) is calculated to quantify the continuous physical demands of 10 construction workers performing both cyclic and non-cyclic tasks across two construction sites over three weeks. Results revealed significant workload variations between task types and work patterns. For instance, stationary tasks ('work without moving') strongly influenced %HRR for rebar workers, while dynamic tasks ('work with moving') had a greater impact on form workers. Additionally, while some daily average %HRR values fell below the 33% threshold, extended high-intensity periods (exceeding 40% HRR for over 30 minutes) posed potential health and safety risks for construction workers. This research demonstrates the potential of long-term HR monitoring to address workload disparities, ensure balanced task allocation, and reduce health risks for construction workers.

Keywords: physical demand, % heart rate reserve, cyclic and non-cyclic work, work load, construction worker.

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1. Introduction

Construction work is inherently labor-intensive, often placing physical demands on workers that exceed their capabilities (Abbe et al., 2011; H. Lee & D.-J. Lee, 2019; Ng & Tang, 2010). The frequently high physical demands can lead to chronic fatigue, reduced productivity, a heightened risk of injury, and early retirement for construction workers (Seo et al., 2016; Yu et al., 2019). In addition, construction tasks are often performed over prolonged periods without adequate rest, in challenging environments such as extreme heat, humidity, or confined spaces. These conditions further increase the risk of on-site construction workers (Wang et al., 2019). In the European Union, 22.5% of all occupational fatalities in 2021 occurred in the construction industry (Eurostat, 2024). According to the Bureau of Labor Statistics, 33% of all occupational injuries and illnesses on U.S. construction sites were related to fatigue and overexertion (Umer et al., 2023; Yu et al., 2019). This evidence underscores the need for systematic measurement and management of physical demands on construction workers to ensure that physical demands remain within acceptable limits in labor-intensive construction environments, thereby sustain productivity without compromising workers' safety and health.

In prior research, a variety of methods have been utilized to measure physical demand, with a focus on quantifying individual responses to specific workloads. These methods often consider factors such as workers' postures (e.g., back bending and twisting), personal attributes (e.g., experience and health condition), and environmental conditions (e.g., atmospheric temperature and humidity) to analyze the physical demand (Li et al., 2019; Martin et al., 1992). However, such studies frequently exclude actual work conditions because they are conducted in laboratory settings rather than on construction sites. Additionally, indirect methods like using a face mask to measure oxygen uptake have been employed to monitor energy expenditure (EE), based on the relationship between oxygen consumption (VO2) and EE to estimate the physical demanding (Garet et al., 2005; Wu & Wang, 2002). This indirect face mask measurement approach is only acceptable in the laboratory environment, since it is inconvenient for the construction workers and might interfere with their normal production work.

Wristband heart rate (HR) health devices have become integral in measuring the continuous and long-term physical demands of workers, making their accuracy and reliability crucial. Systematic investigations into the precision of these devices have been conducted, using wristband-type HR sensors. For instance, Kirk and Sullman (2001) conducted pioneering research in 2001, demonstrating the correlation between heart rate indices and physical strain by analyzing the physical performances of choker setters in New Zealand. This study laid the groundwork for subsequent enhancements in the field. Ismaila et al. (2013) introduced a novel method that utilizes variations in heart rate to assess cardiovascular strain among sawmill workers, relating it to their physical workloads. This study not only estimated the physiological strain of the workers but also provided recommendations for redesigning work content to mitigate health risks. Continuing this trend, Gatti et al. (2014) explored the connections between workforce performance and physical strain, using HR and relative HR as indicators. With advancements in wearable health technologies, Hwang et al. (2016a) and Hwang and Lee (2017) employed the Heart Rate Reserve (%HRR) – a relative measurement of physical demand – to continuously monitor and understand the physical demands faced by construction workers. Recent studies have increasingly utilized wristband-type wearable sensors to collect physiological signals from construction workers, using these as inputs for the %HRR indicator (Chen & Tserng, 2022; Hashiguchi et al., 2020; Lee et al., 2021; Wang et al., 2022). This approach has facilitated comprehensive assessments of physical health for workers across various construction roles.

In this study, %HRR is selected as the principal metric to assess the physical demands of construction workers, offering significant advantages for evaluating dynamic and physically demanding environments. Unlike absolute HR, which can fluctuate due to various factors such as environmental conditions, emotional states, and health variables, %HRR normalizes heart rate by anchoring it between an individual's resting heart rate ($HR_{resting}$) and maximum heart rate (HR_{max}). This normalization provides an accurate assessment of physiological strain relative to the personal capacity, crucial for construction settings where task intensities vary significantly (Hwang & Lee, 2017; Wu & Wang, 2002). The use of %HRR is particularly advantageous for monitoring over extended periods, capturing sustained exertions that are typical in construction work (Fecchio et al., 2019; Gupta et al., 2014). This method not only allows for detailed analysis of varying stress levels but also adjusts for individual differences in fitness and cardiovascular health, ensuring that exertion assessments are personalized and reflective of true physical demand (Eguchi et al., 2011; Ghafoori et al., 2023b). Importantly, studies have demonstrated that %HRR has a robust correlation with physical workload and energy expenditure, more so than absolute HR (Coenen et al., 2018; Hashiguchi et al., 2020). This correlation is important in construction work where precise energy management is key to preventing overexertion and enhancing productivity, making %HRR a valuable tool for effective workload management in the construction industry. As such, the %HRR approach was widely applied to estimate the intensive and demanding work during the construction (Coenen et al., 2018; Merkus et al., 2019; Wang et al., 2019).

This study explores the application of wristband wearable HR monitors to measure the high physical demand tasks of on-site construction workers (Abuwarda et al., 2024; Arias et al., 2023; Cao et al., 2023; Chen et al., 2023). However, previous research is limited to individual factors. For example, the traditional energy expenditure measurements often fail in the construction context due to the highly variable and physically intensive nature of the on-site tasks (Hwang et al., 2016b), which includes a diverse array of tasks that change frequently and unpredictably. And the previous research often relied on invasive sensors such as the mask or chest band to measure the physical demands of construction workers, which may interfere with their performance and comfort (Abdelhamid & Everett, 2002; Nwaogu & Chan, 2021; Tavakoli et al., 2020; Wang et al., 2024; Whitfield et al., 2014). Additionally, many studies were conducted in controlled indoor environments rather than real field conditions, limiting their applicability to dynamic construction sites (Fang et al., 2015; Seo et al., 2015a, 2015b). Moreover, prior work has not adequately addressed the differences between cyclic and non-cyclic work patterns, nor have they investigated physical demand variations over extended cycles. Understanding these patterns is crucial because cyclic work involves repetitive tasks that, if poorly distributed, may lead to cumulative fatigue or uneven workload allocation, potentially impacting worker safety and productivity. Conversely, non-cyclic work typically involves irregular and unpredictable tasks, making it more challenging to manage workloads effectively and prevent excessive physical demand. Investigating these patterns helps to identify whether cyclic tasks are consistently well-allocated over time and whether non-cyclic tasks introduce significant variations in physical demand. However, most existing studies have focused on short-term recordings of physical demand, which fail to capture these critical variations, leaving a gap in understanding how workload patterns evolve over longer periods (Hoozemans et al., 2001; Nasirzadeh et al., 2020). Furthermore, previous research has not comprehensively explored the relationship between %HRR and workload, nor thoroughly examined the potential correlations between physical demand and working periods (e.g., morning vs. afternoon). Investigating how different workloads affect %HRR values is critical for understanding which tasks (i.e., work with moving, work without moving and idling) place the highest physical demands on workers, allowing for better task allocation and management strategies to minimize overexertion and improve overall efficiency. Similarly, analyzing the correlation between physical demand and working periods can help identify time-of-day effects, such as increased fatigue or reduced performance in the morning or in the afternoon, which may inform adjustments to work schedules or breaks to enhance worker safety and productivity. The lack of such in-depth analyses leaves gaps in understanding how to optimize workload management and mitigate health risks in the construction industry.

Recognizing these challenges, the present research regards the feasibility of wristbands as a practical solution for continuous HR monitoring without causing discomfort to the workers – a notable advantage over other HR monitoring devices such as chest straps (Gatti et al., 2014; Migliaccio et al., 2012). By conducting a case study, this study examines the potential of wristbands to capture significant variations in the high physical demands of construction workers over an extended period. The study makes significant contributions to the field in several ways:

1) It introduces an innovative approach to studying workload disparities over extended time periods, enabling the identification of patterns and inconsistencies in cyclic and non-cyclic task arrangements: (1) analyzing the physical patterns of the same worker across different weeks under cyclic work to determine whether workloads are well-allocated and show consistent patterns; and (2) comparing the workloads of different workers during the same week to assess workload allocation and the influence of worker experience. By understanding these patterns, this study seeks to improve workload management strategies and ensure fairness and efficiency in task assignments.
2) It provides a methodological framework for correlating %HRR with task types, offering a quantifiable basis for evaluating physical demands in on-site construction environments. This study incorporates GoPro-recorded videos from workers to correlate %HRR values with specific work tasks. Tasks are categorized into three types – stationary work type (work without moving), dynamic work type (work with moving), and idling – based on video analysis. By linking %HRR values to these task types, this study provides a detailed explanation of the physical demands experienced by construction workers and identifies variations across different types of construction tasks. These findings can offer actionable insights for workload distributions based on task characteristics.
3) Analyzes differences in physical demand based on worker roles (e.g., rebar workers and formwork workers), working periods (morning and afternoon), and analysis time intervals (5 s or 1 h). The analysis incorporates both short (e.g., 5 s) and long (e.g., 1 h) data intervals to account for the variability of %HRR responses and avoid distortions caused by overly short (e.g., 1 s) or overly long (e.g., 1 day) sampling periods. This thorough analysis ensures a comprehensive understanding of how physical demand varies with time, task type, and worker role.

The primary goal of this study is to assess the viability of %HRR measurement approaches for evaluating workloads through continuous on-site monitoring and to establish correlations between %HRR-induced physical demand changes and workload estimations. Prolonged HR monitoring provides a more comprehensive understanding of how physical demands vary over time, capturing both short-term fluctuations and long-term patterns in cyclic and non-cyclic tasks. This insight is critical for identifying workload disparities, such as cumulative fatigue from repetitive cyclic tasks or unbalanced allocation of non-cyclic tasks among workers. These findings allow construction managers to dynamically adjust task schedules, ensuring workloads are distributed equitably and reducing health and safety risks associated with overexertion. The non-invasive and cost-effective features of the wristband HR recording method not only simplify its adoption in practice but also makes it an attractive option for application in the construction industry.

After the Introduction, Section 2 illustrates the procedures for on-site data collection and physical demand measurement. Following the case study, the results concerning the physical demand patterns and relations between %HRR and workloads are discussed in Section 3. Finally, concluding remarks are given in Section 4.

2. Methodology

2.1. Processes of on-site data collection

In this study, HR data were collected over three weeks from 10 construction workers, with five workers engaged in cyclic work schedules at the FoTan site and the remaining five following non-cyclic schedules at the St. Paul site. This selection was aimed to include workers from different work patterns (cyclic and non-cyclic) for workload analysis. Previous research has consistently demonstrated the validity of employing modest sample sizes in studies focusing on the physical demands of construction work. For instance, studies such as Anwer et al. (2023), Ghafoori et al. (2023a), Hwang and Lee (2017), Lee et al. (2017) have effectively used similarly small groups of 10–15 workers to gather the HR of construction workers, establishing a precedent for the sample size used in this study. HR data were collected from workers in demanding roles such as rebar fixers and form workers. The cyclic HR data gathering occurred at the FoTan construction site from 8 September 2018 to 15 December 2018, covering a monitoring period of 14 weeks. Non-cyclic data were collected from a school building at the St. Paul site from 2 February 2019 to 9 March 2019, which lasted five weeks. This design was intended to comprehensively analyze workload across different work patterns and conditions, and also to determine whether the workload performance of the same individual under the same work pattern remains consistent over different time periods. However, several issues occurred during the collection process, including: 1) heavy rains in Hong Kong during October and February that delayed testing; 2) some noise in the datasets due to workers improperly equipping the data collection devices, leading to missing or discontinuous HR data; 3) some workers moving to another construction site, causing discontinuities in HR data collection; and 4) some workers removing the data collection device during rest times and forgetting to wear them back, resulting in missing data during the monitoring period. Consequently, more reliable data (three weeks in total: 13–18 November 2018, 3–8 December 2018, and 4–9 March 2019, as shown in Table 1) from the 10 construction workers were analyzed in this study.

In Table 1, detailed descriptions of the data collected are provided, including workers' ages, work types, site information, and daily average temperatures at each site. To assess the influence of environmental factors on workers' physical performance, this study considered daily average air temperatures sourced from the nearest Hong Kong Observatory (HKO) weather stations to each site – Sha Tin (SHA) station for the FoTan site and Happy Valley (HPV) station for the St. Paul site as shown in Figure 1. From the data illustrated in the attached Figure 1a, it is evident that during the measurement periods (highlighted in the figure), the maximum temperature difference is only 3.7 °C, ranging from 23.4 °C in November to 19.7 °C in March. This minor variation suggests that the impact of temperature on the physical demands of cyclic or non-cyclic work schedules can be considered negligible. Moreover, the daily average temperatures during December and March (highlighted periods) showed a consistent pattern, with peak temperatures reached on the second day of measurement, followed by a rapid decline over the six-day period (ΔT = 1.8 °C). The similarity features shown in average temperatures between these two measurement periods allowing to neglect the external influence of temperature on physical demands. It is noteworthy that although the temperature patterns during the different measurement periods for the same construction worker (i.e., R#1-1) in November and December were not completely identical, the small difference in average temperature (1.9 °C) between these periods further supports the conclusion that the physical demanding performance of the subjects can be considered independent of external temperature variations.

Table 1 provides detailed descriptions of the data collected, including workers' ages, work types, site information, and collection periods at each site. This study analyzed cyclic work schedules at Site #1 (the FoTan site) and non-cyclic work schedules at Site #2 (the St. Paul site) to compare patterns of individual physical performance of workers. Among the factors considered, age is identified as the empirical factor that influences physical demands. In Table 1, work types are identified by the first capital letter in the worker number; 'R' denotes rebar fixers, and 'F' represents form workers. Site information is indicated by the first number and a capital letter (e.g., '#1' for the FoTan site – cyclic work, and '#2' for the St. Paul site – noncyclic work). The second number specifies the number of workers in each category. HR data was collected for a full week for each worker. Notably, worker R#1-1 participated in the data collection during two distinct weeks.

Before starting the data collection processes, all participating construction workers were required to provide their personal information, including age, years of employment, work type, and health conditions. The inclusion criteria for this study were: 1) age under 60; 2) employment as either a rebar or formwork worker; and 3) no history

Table 1. Detailed information on data collection

Site	Work type	Worker ID#	Age	Collection dates	Data availability
Site #1 (FoTan)	Rebar	R#1-1	40	13 Nov. 2018 to 18 Nov. 2018, and 3 Dec. 2018 to 8 Dec. 2018	2 weeks
		R#1-2	31	3 Dec. 2018 to 8 Dec. 2018	1 week
	Formwork	F#1-1	43		
		F#1-2	35		
		F#1-3	29		
Site #2 (St. Paul)	Rebar	R#2-1	50	4 Mar. 2019 to 9 Mar. 2019	1 week
		R#2-2	49		
	Formwork	F#2-1	40		
		F#2-2	40		
		F#2-3	28		

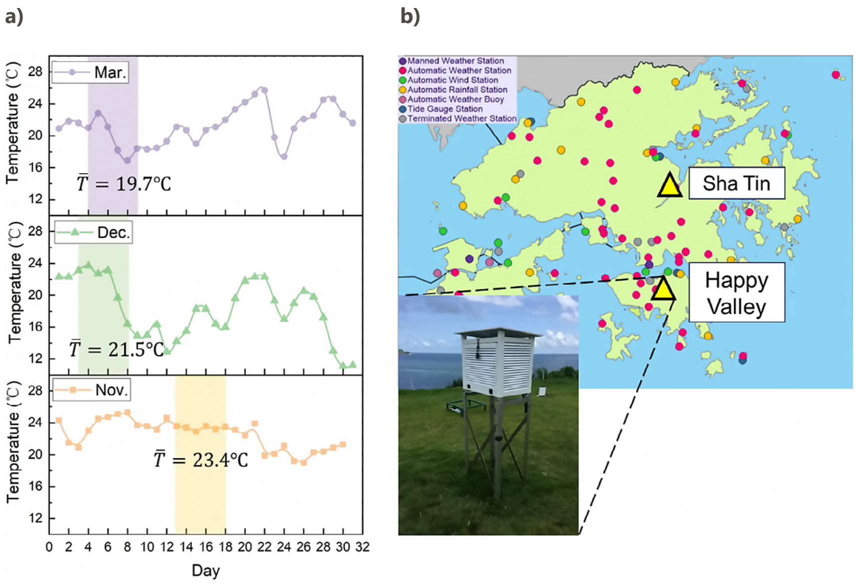

Figure 1. a – daily mean air temperature during Nov., Dec. and Mar. The highlighted bar shows the HR recording period; b – the locations of two HKO observatory weather stations

of heart disease or high blood pressure. Several factors were considered in the selection of data collection devices, including comfort, privacy protection, storage capacity of the wristband, and battery life. Consequently, the Apple Watch Series 4, as shown in Figure 2, was chosen for HR data collection. Additionally, a GoPro camera was attached to the worker's chest for sub-task analysis (in Figure 3). Workers were assured that the lightweight wristband would not interfere with their normal work activities and were informed that they could discontinue participation if they experienced any discomfort. They were also assured that their private information would be kept confidential and that their HR and %HRR data would be used solely for analyzing physical demands. At the end of each day, all HR data were uploaded to an internal server at the Hong Kong Polytechnic University.

2.2. Physical demand measurement

Based on the recorded HR data, %HRR can be calculated by Eqn (1) to describe the physical demands of workers (Hwang & Lee, 2017; Kirk & Sullman, 2001):

$$\%HRR = \frac{HR_{\text{working}} - HR_{\text{resting}}}{HR_{\text{maximum}} - HR_{\text{resting}}} \times 100\%, \quad (1)$$

where HR_{resting} is equal to the resting heart rate [bpm]; HR_{working} means the average value of heart rate while working [bpm]; and HR_{maximum} describes the maximum heart rate calculated by the formula (220 – 0.7*age) [bpm] (Jebelli et al., 2018; Kirk & Sullman, 2001; Westerterp, 2017). To clarify, the term 'HR resting' in this study refers to the heart rate measured after a period of rest (around 10–20 mins), not immediately following work-related activities. Specifically, the present study measures the resting heart rate 10 minutes into each worker's designated rest period.

Figure 2. Sample of the Apple Watch Series 4[1], which was used to capture the heart rate of construction workers

Figure 3. Rebar workers were wearing Apple Watches while working on the site

[1] https://support.apple.com/en-hk/HT204666

This measurement approach aligns with prior research (Benes et al., 2013; de Araújo et al., 2017; Matsuura et al., 2019), which supports that over 80% of peak heart rate recovery occurs within the first 2–3 minutes after cessation of physical activity (Savin et al., 1982). Consequently, this timing ensures that the heart rate has stabilized, providing a reliable measure for assessing the baseline heart rate in a controlled, restful state. Previous studies adopted different %HRR limits to describe the physical demands, such as 33%HRR and 40%HRR. Gupta et al. (2014) applied the threshold of 33% to categorize %HRR into high (>33%HRR) and low (≤ 33%HRR) categories for a construction worker who works for 8 hours per day, and the average %HRR below 33%HRR can be considered the level of moderate physical demand at which the work contents are well-organized. Also, Hwang and Lee (2017) defined that the %HRR value exceeding 40% and lasting for 30 minutes may also influence the worker's health during on-site work. This study adopted 33%HRR (averaged %HRR) and 40%HRR (continuous %HRR) as the limits of workers' physical demand. Figure 4 depicts the flowchart of the proposed workload evaluation method for construction workers.

3. Results and discussions

3.1. Workers' physical demand patterns based on %HRR

This study investigated workers' %HRR patterns through long-term HR monitoring and %HRR calculations, highlighting the potential of HR-based physical demand analysis. Figure 5 presents the daily %HRR of workers at the FoTan site, including two rebar workers and three form workers. For the rebar workers on a 6-day cycle, as shown in Figure 5a–5c, HR data for worker R#1-1 were collected during two different weeks: 13–18 November, 2018 (Figure 5a) and 3–8 December, 2018 (Figure 5b). HR data for worker R#1-2 were also collected during 3–8 December, 2018 (Figure 5c), when both workers, R#1-1 and R#1-2, performed similar tasks as members of the same team. As a result, their physical demand patterns were expected to be similar. However, the HR data for day1 and day6 of R#1-1's first week (Figure 5a) were highly affected by signal noise and were therefore excluded from the analysis. For form workers on the 6-day cycle, as shown in Figure 5d–5f, HR data were collected for three workers: F#1-1 (Figure 5d), F#1-2 (Figure 5e), and F#1-3 (Figure 5f), all during the week of 3–8 December, 2018. Notably, no form workers were scheduled for testing on day 3, day 4, and day 6, according to the site schedule. During the working days (day 1, day 2, and day 5), the three form workers performed similar tasks.

As previously described, 33% HRR is considered the threshold for high physical demand during continuous work, indicated by red lines in Figure 5. The results show that the majority of average %HRR values for both rebar and form workers during a typical cyclic construction schedule remains below the 33% threshold. This is consistent with the observations from a previous study which monitored physical demands in construction workers by %HRR over several days (Chen & Tserng, 2022; Lunde et al., 2016). The differences between these studies might be attributed to variations in the specific tasks performed by workers, or the intensity of the physical activities involved. Furthermore, the earlier study found significant associations between physical demand and HR at work and factors such as age, but not with musculoskeletal pain, or subjective general health. These aspects were not directly addressed in Figure 5, suggesting potential areas for future research to explore how these factors might interact with %HRR in different construction professions. Certain exceptions are observed, such as R#1-1's day 5 in the first week (Figure 5a) and R#1-2's day 2 (Figure 5c), where average %HRR exceeded the threshold, indicating high physical demand levels. These excessive demands are likely due to unusually intense work performed without adequate rest.

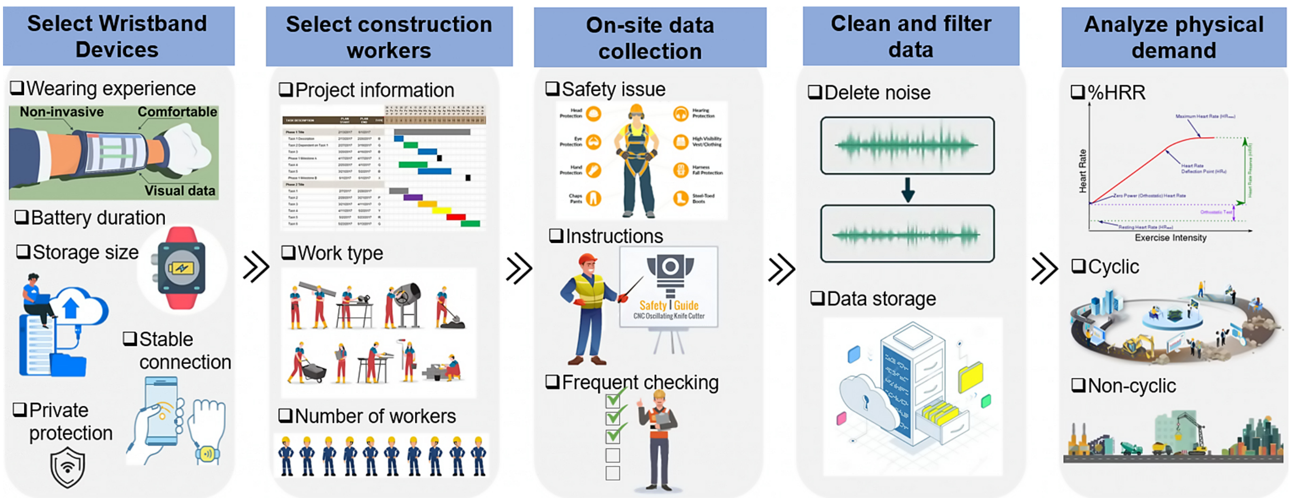

Figure 4. Data collection flowchart

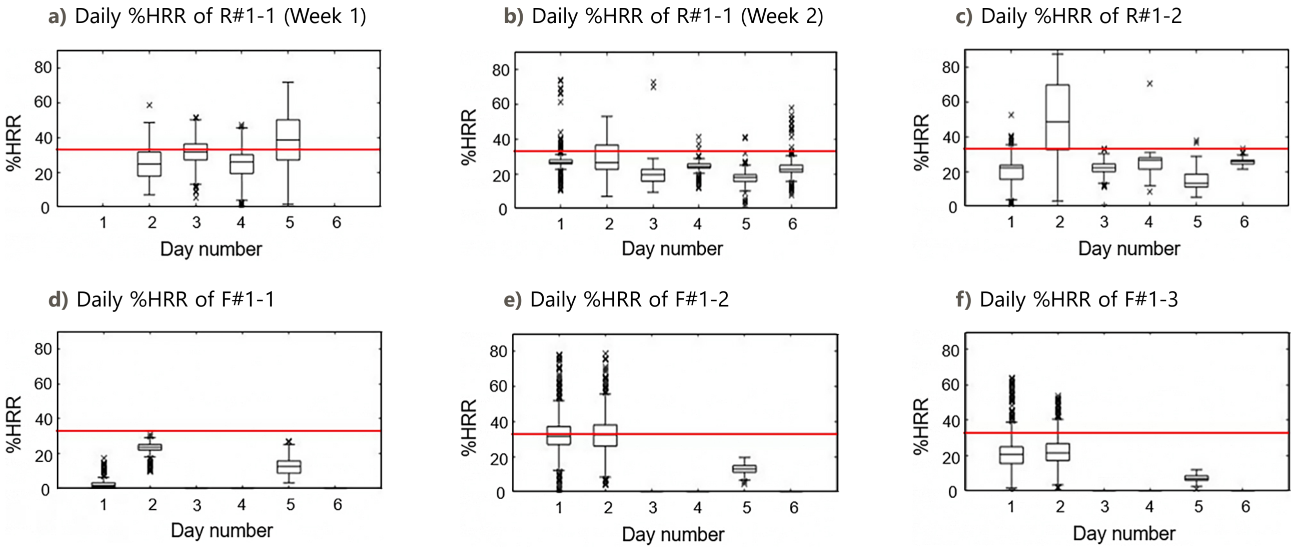

Figure 5. %HRR of workers in the FoTan site: a – worker R#1-1 in the first week; b – worker R#1-1 in the second week; c – worker R#1-2; d – worker F#1-1; e – worker F#1-2; f – worker F#1-3

From Figure 5, the trends in average %HRR values for cyclic work show notable similarities. For instance, the rebar workers both exhibited high physical demands on day 2, while the form workers showed relatively low physical demands on day 5. These results indicate that workers' demands tend to synchronize when they perform tasks collaboratively. The workloads and resource arrangements for form workers appear reasonable, as there were no highly physically demanding days during the investigation period. However, no consistent relationship was observed for the same rebar worker across different weeks (R#1-1 and R#1-2), suggesting that their tasks were not strictly repeated week by week. This highlights potential issues with on-site work arrangements. Ideally, if tasks were evenly distributed over the week, workers would not experience high %HRR values, and their average %HRR would remain stable. However, the data from Figure 5a and Figure 5c reveal high physical demands on specific days. Notably, for R#1-1 (Week 1) on day 5 and R#1-2 on day 2, the average %HRR exceeded 40%, indicating prolonged periods of physical exertion beyond safety limits. Such conditions pose significant risks to workers' health, potentially leading to injuries or cardiovascular issues under severe circumstances.

Furthermore, the %HRR pattern for an individual worker varied significantly across weeks. For example, R#1-1's average %HRR in the first week (Figure 5a) is notably higher than in the second week (Figure 5b). This discrepancy can be attributed to a vacancy among rebar workers during the first week at the FoTan site, requiring the remaining workers to increase their workload to meet installation demands. This compressed rest time led to higher physical demands for R#1-1 in the first week. In contrast, during the second week (Figure 5b), R#1-1 worked alongside R#1-2 (Figure 5c), performing similar tasks at the same site. As a result, their average daily %HRR patterns were comparable and stable, except on day 2, where both workers experienced a peak in %HRR. On the other hand, the form workers in Figure 5d–5f demonstrates consistent %HRR patterns, with slightly elevated values on day 2 and lower values on day 5. Additionally, no excessive physical demand was observed during this week. The lower %HRR value for F#1-1 on day1 can be explained by an extended idling period compared to the other workers.

Figure 6 presents the daily %HRR of workers at the St. Paul site from 4 March to 9 March, 2019, including two rebar workers and three form workers. The %HRR patterns for R#2-1 (Figure 6a) and R#2-2 (Figure 6b) differ, with R#2-1 showing relatively stable daily %HRR patterns, while R#2-2 exhibits more fluctuations. Specifically, R#2-1 experienced two days of high physical demands (day 1 and day 2), whereas R#2-2 had three excessive workload days (day 1, day 2, and day 5). In contrast, the %HRR patterns for the form workers who performed similar tasks appear consistent, with balanced physical demands across the days, as shown in Figure 6c–6e.

As shown in Figure 6, %HRR patterns vary not only due to personal differences but also by the tasks performed. For example, R#2-1 and R#2-2 exhibited highly variable %HRR patterns because their activities included heavy workloads such as frequent squatting and upper limb movements that compress the chest. Posture significantly impacts the amount of heart strain, measured as %HRR. Similar conclusions were reached by Tsioras et al. (2022), which also illustrated that certain postures, including (i) stooping, (ii) flexed stooping, (iii) squatting, and (iv) half kneeling, may require greater physical demands. Additionally, the %HRR of R#2-1 and R#2-2, who were older workers (50 and 49 years old, respectively) than other participants, also showed higher variation than those of younger workers, which may result from age effects on cardiovascular loads (Hwang et al., 2016a; Lunde et al., 2016). %HRRs of all formwork workers (i.e., F#2-1, F#2-2, and F#2-3) showed frequent changes because these sub-

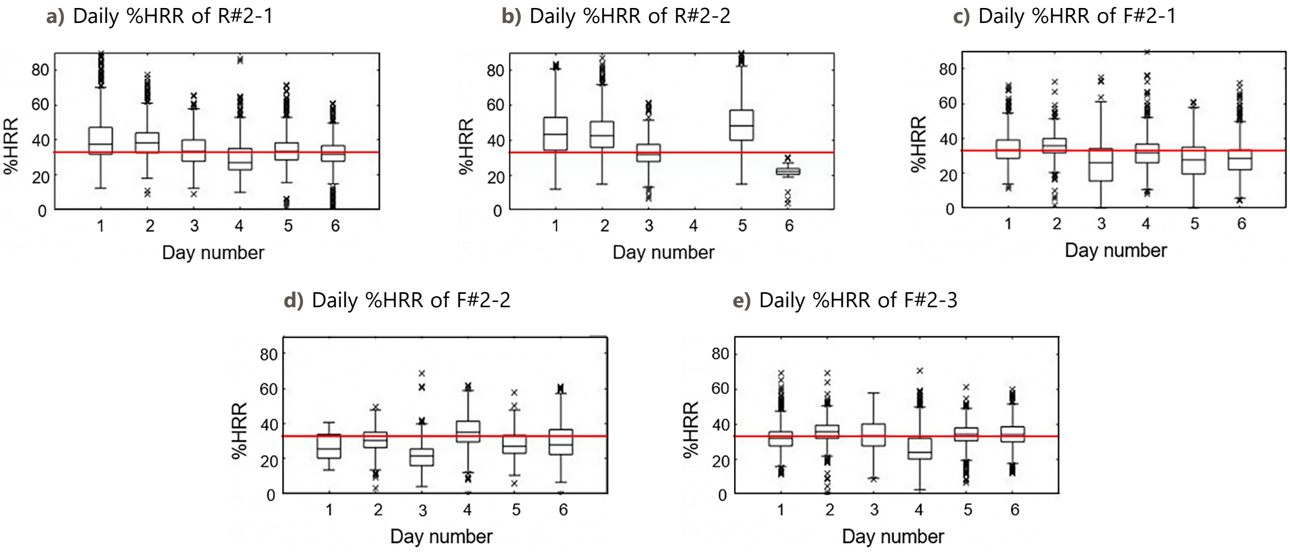

Figure 6. %HRR of workers in the St. Paul site: a – worker R#2-1; b – worker R#2-2; c – worker F#2-1; d – worker F#2-2; e – worker F#2-3

jects worked outdoors in high temperatures and their activities involved a wide range of movements, including ladder climbing and slab moving. This analysis demonstrates that HR monitoring can be useful for approximately assessing a worker's physical workload from their tasks.

Notably, worker F#2-2 displayed balanced duration percentages for each type of work, resulting in a lower average %HRR compared to the other workers. According to Table 1, F#2-2 is an experienced worker, which likely contributed to the ability to balance work types effectively and avoid excessive demands. The same conclusions also given by Chen and Tserng (2022). This observation suggests a potential strategy for site managers: assigning more complex or skill-intensive tasks to experienced workers while allocating fewer demanding tasks to less experienced workers. Such an approach can maintain high productivity levels while protecting workers' health, thereby significantly improving on-site work efficiency. To summarize, the results indicate that workers performing the same tasks (e.g., team members or workers in the same trade executing similar tasks on the same day) exhibit similar %HRR patterns. This provides evidence for the potential of %HRR-based physical demand measurement in relation to workloads. However, unusually low or high %HRR values were also observed, underscoring the limitations of relying solely on %HRR pattern analysis to assess physical demands. To address this, the authors conducted an in-depth analysis of workers' task types to examine the relationship between %HRR and workloads, further exploring the utility of %HRR-based physical demand measurement.

3.2. Relationship between %HRR and workloads

For an in-depth understanding of workers' workloads, the authors analyzed their work tasks using video extracted from GoPro cameras worn on the workers' chests. Tasks were categorized into three types based on physical movements

***Type 1:** Dynamic tasks – tasks involving movement, such as transporting materials, lifting tools, and walking to workplaces.

***Type 2:** Stationary tasks – tasks performed without significant movement, such as rebar fixing and bending.

***Type 3:** Idling – activities such as drinking or resting.

The percentage duration of each task type was analyzed. Due to noise and missing video data, only the data presented in Table 2 were used for task analysis to infer workloads. The data presented in Table 2 reveals important insights into the relationship between task types, worker roles, and physical demand as measured by %HRR. For rebar workers who spent a higher proportion of their time on stationary tasks (type *2) generally exhibited higher %HRR averages, and for some instance it may occur exceeding physical demand (e.g., R#2-2 on 5 and 8 March with 68.07% and 52.18% on stationary tasks, the average %HRRs are 43.02% and 48.86%, respectively). However, dynamic tasks (type *1) also resulted in high %HRR values for some cases, as observed for R#2-2 on 4 and 5 March, where 72.77% and 66.99% of the time were spent on stationary tasks, leading to a %HRR average of 43.02%. However, stationary tasks (type *2) also resulted in high %HRR values for some instance, as observed for R#2-2 on 5 March, where 68.07% of the time was spent on stationary tasks, leading to a %HRR average of 38.20% and 38.95%, respectively. The similarity conclusions can be made from the form workers. These findings suggest that both dynamic and stationary tasks can impose significant physical demands on construction workers, depending on the intensity of the work involved. Workers with a higher proportion of idling time (type *3) generally showed lower %HRR values, indicating that extended idling periods significantly reduce physical demand. For example, R#1-1 on 15 November had an idling duration of only 1.94%, resulting in an average %HRR of 27.6%, while on 16 November, the idling duration increased to 18.26%, leading to a slightly lower %HRR of 24.03%. This correlation highlights the critical role of rest periods in managing physical demands.

Rebar workers generally experienced higher variability in %HRR compared to form workers. The largest variation occurred in R#2-2's %HRR values varied between 27.63% and 48.86% (Δ = 21.23%), reflecting the greater physical demands of rebar-related tasks. In contrast, form workers displayed more stable %HRR patterns, the largest variation can be found in F#2-1, whose %HRR values ranged from 22.64% to 37.88% (Δ = 15.24%). Balanced task durations appeared to reduce variability in %HRR. F#2-2, for instance, demonstrated balanced distributions of type *1 and type *2 tasks, resulting in moderate %HRR averages ranging from 20.74% to 34.00% (Δ = 13.26%). In contrast, workers with disproportionate task durations, such as R#2-2 on 5 March, who spent 68.07% of their time on stationary tasks, showed much higher %HRR averages, peaking at 43.02%. These findings suggest that balancing task durations effectively can mitigate excessive physical demand and improve worker efficiency. The data further indicates that experienced workers are better able to manage workloads, as shown in F#2-2, whose efficient task distribution correlated with lower %HRR values compared to other workers. Inexperienced workers, on the other hand, may lack the ability to adjust their pace or tasks effectively, leading to greater variability and higher physical demand, as seen in R#2-2's data.

Table 2. Detailed information on data collection

Worker	Date	% Type of task			%HRR	
		*1 [%] (Work with moving)	*2 [%] (Work without moving)	*3 [%] (Idling)	Average [%]	Standard deviation
R#1-1	14 Nov.	32.10	48.38	19.52	27.05	11.14
	15 Nov.	42.68	55.38	1.94	27.6	7.92
	16 Nov.	25.09	56.65	18.26	24.03	5.61
	3 Dec.	26.85	56.48	16.67	25.33	3.35
	4 Dec.	28.62	63.60	7.78	25.29	21.88
	6 Dec.	38.89	37.72	23.39	23.33	6.41
R#2-1	4 Mar.	72.77	24.42	2.81	38.20	8.66
	5 Mar.	66.99	28.71	4.30	38.95	6.98
	6 Mar.	49.26	32.82	17.92	33.16	7.42
	7 Mar.	60.26	7.65	32.09	25.75	7.8
	8 Mar.	62.18	34.67	3.15	33.00	6.47
	9 Mar.	48.24	47.75	4.01	32.15	5.6
R#2-2	4 Mar.	69.51	30.18	0.31	42.23	13.39
	5 Mar.	27.68	68.07	4.25	43.02	11.09
	6 Mar.	33.80	61.78	4.42	27.63	8.53
	8 Mar.	45.04	52.18	2.78	48.86	12.61
F#2-1	4 Mar.	29.80	63.54	6.66	32.83	6.98
	5 Mar.	42.55	50.30	7.15	37.88	9.00
	6 Mar.	45.40	48.23	6.37	22.64	9.31
	7 Mar.	68.65	30.09	1.26	32.40	8.73
	8 Mar.	12.61	72.60	14.79	24.05	7.33
	9 Mar.	21.28	70.21	8.51	25.68	7.86
F#2-2	5 Mar.	37.57	56.89	5.54	31.43	8.03
	6 Mar.	14.35	60.35	25.30	20.74	10.01
	7 Mar.	37.04	28.52	34.44	34.00	7.04
	8 Mar.	20.90	52.95	26.15	27.56	2.01
	9 Mar.	34.49	52.61	12.90	28.68	8.01
F#2-3	4 Mar.	25.90	74.10	0	32.58	7.81
	5 Mar.	44.96	54.55	0.49	35.31	6.43
	6 Mar.	40.64	52.00	7.36	33.1	7.85
	7 Mar.	22.68	71.68	5.64	23.96	7.58
	8 Mar.	28.41	71.59	0	34.57	6.66
	9 Mar.	33.58	66.42	0	33.17	7.68

Some days demonstrated extremely high %HRR values that likely exceeded safe threshold, as shown in bold in Table 2. According to Ghafoori et al. (2023b) and Norton et al. (2010) categories of physical activity intensity, discussed in the methodology section, this indicates excessive physical demand. Therefore, interventions are necessary to reduce the physical demands on these workers. This demonstrates the importance of continuously measuring HR during ongoing work and balancing workloads to prevent overload. To this end, implementing a flexible work-rest schedule with frequent short breaks can help avoid consistently high physical demands. Additionally, physically demanding tasks should be distributed as evenly as possible throughout the workdays to prevent excessive physical demands on any given day.

To explore the relationship between %HRR and work types, all daily data were divided into hourly data points, allowing for both hourly and daily analyses of %HRR-based physical demand. Hourly %HRR data were predominantly used for in-depth analysis (Çalıskan & Çaglar, 2010; Olson & King, 2012; Sahu et al., 2013). Figure 7 illustrates the relationship between %HRR and the three work types for all workers, while Figure 8 and Figure 9 focus on rebar workers and form workers, respectively. The results revealed that idling (type *3) consistently resulted in lower %HRR values for both rebar and form workers, as shown in Figure 7c, Figure 8c, and Figure 9c. This negative correlation between %HRR and the duration of idling time supports the feasibility of %HRR-based physical demand measurement, as longer idling durations indicate lower workloads. In Figure 7a, representing dynamic tasks, the average %HRR values are distributed across a range of duration percentages, with the linear trendline showing minimal variation. The associated distribution figure indicates that most workers spent between 20% and 60% of their time on dynamic tasks, with a slight peak around 40%. A moderately concentrated distribution of average %HRR values can be observed, with most workers' %HRR clustered around 20% to 30%, indicating that dynamic tasks typically induce moderate physical demand. In Figure 7b, for stationary tasks, the scatter plot reveals some variability in average %HRR as the duration percentage increases. The linear trendline suggests a weak positive relationship, where longer durations of stationary tasks may slightly increase %HRR. The distribution figure shows a wider spread in the duration percentages, with peaks occurring around 50%, reflecting greater variation in how workers allocated time to stationary tasks. The average %HRR values are more spread out compared to dynamic tasks, with a wider range between 20% and 35%, indicating higher

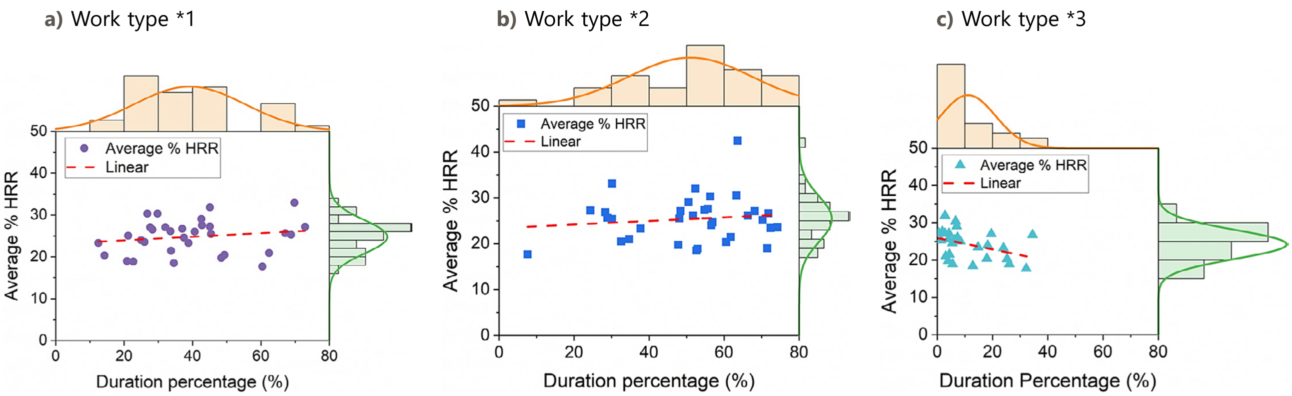

Figure 7. Relationship between average %HRR and the duration percentage of work types for all workers: a – type *1 (dynamic tasks); b – type *2 (stationary tasks); c – type *3 (idling)

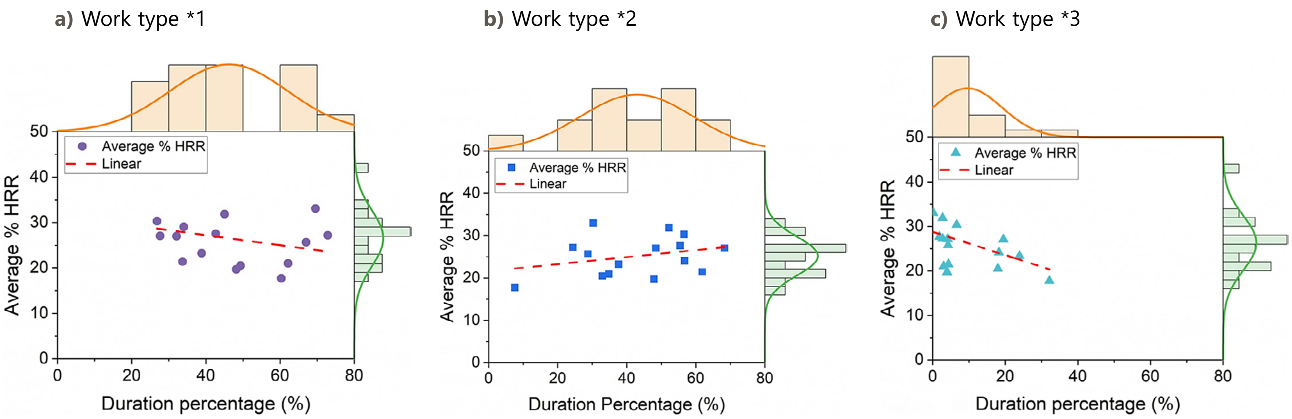

Figure 8. Relationship between average %HRR and the duration percentage of work types for rebar workers: a – type *1 (dynamic tasks); b – type *2 (stationary tasks); c – type *3 (idling)

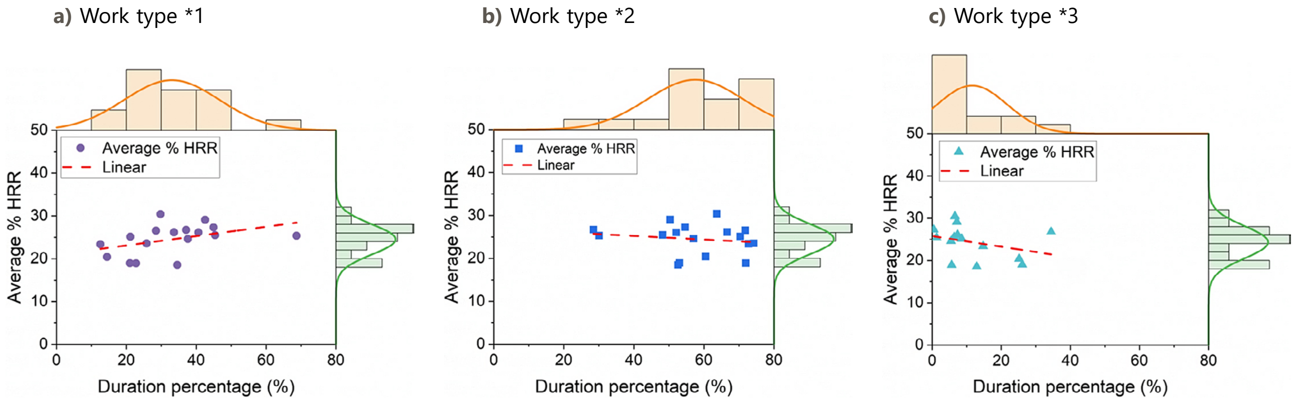

Figure 9. Relationship between average %HRR and the duration percentage of work types for form workers: a – type *1 (dynamic tasks); b – type *2 (stationary tasks); c – type *3 (idling)

variability in physical demand for stationary tasks. In Figure 7c, the scatter plot exhibits a clear negative correlation between the duration percentage of idling and average %HRR, as shown by the downward-sloping trendline. Workers with longer idling periods consistently displayed lower %HRR values. The distribution figure shows a sharp decline in the proportion of workers with higher idling times, with most idling durations concentrated below 30%. The average %HRR values for idling tasks are tightly concentrated between 20% to 30%, highlighting the minimal physical demand associated with this task type. Overall, dynamic tasks show moderate %HRR with slightly increase trends, stationary tasks exhibit more variability in %HRR with a slight positive trend, and idling tasks consistently result in low %HRR values as duration increases.

In Figure 8a, the average %HRR values show decrease trend across different duration percentages for dynamic tasks. Most rebar workers spend between 20% and 60% of their time on dynamic tasks, with a peak around 45%. The average %HRR values for dynamic tasks are clustered around 15% to 35%, indicating that dynamic tasks typically generate moderate physical demands. In Figure 8b, a weak positive correlation between the duration percentage and the average %HRR in stationary tasks. This suggests that longer durations of stationary tasks may slightly increase the physical demand for rebar workers. The duration percentages are broadly distributed compared to the dynamic tasks, with notable peaks around 42%. The average %HRR values for stationary tasks are more concentrated, reflecting lower variability in physical demand for stationary tasks. In Figure 8c, a clear negative correlation between the duration percentage of idling tasks and the average %HRR can be found. This indicates that increased time spent idling consistently results in lower %HRR values, highlighting the minimal physical demand associated with idling.

In Figure 9a, a weak positive correlation between the duration percentage of dynamic tasks and the average %HRR can be obtained. This indicates that longer durations of dynamic tasks are associated with a slight increase in %HRR for form workers. Most of form workers spent between 20% and 50% of their time on dynamic tasks, with a peak around 34%. The average %HRR values are more concentrated between 20% and 30%. In Figure 8b, the stationary tasks show slightly decrease relationship between the duration percentage and the average %HRR. The task durations are relatively higher than that from the dynamic tasks, with peaks around 58%. The average %HRR values are primarily distributed between 20% and 30%. In Figure 8c, the idling tasks demonstrates a clear negative correlation between the duration percentage and the average %HRR. This indicates that longer idling periods are consistently associated with lower %HRR values.

In conclusion, dynamic tasks (type *1) and stationary tasks (type *2) impacted %HRR differently for rebar and form workers. For rebar workers, a higher duration percentage of type *2 tasks led to an increase in average %HRR, as shown in Figure 8b. In contrast, for form workers, type *1 tasks dominated the average %HRR values, as shown in Figure 9a. These differences reflect the nature of their tasks: type *2 tasks for rebar workers include physically demanding activities such as rebar fixing and bending, while type *1 tasks for form workers involve demanding activities such as form lifting. These observations highlight the significant influence of specific task types on %HRR and demonstrate the feasibility of %HRR-based physical demand measurement for evaluating workloads across different construction roles and tasks.

3.3. Differences in physical demand among the worker types and working periods

This research collected data from 10 workers over three weeks to analyze differences in physical demands among worker types (rebar and formwork) and across working periods (morning and afternoon). To justify conclusions about these differences, a student t-test was performed, with a 95% confidence interval, to compare %HRR values in the specified conditions. Regarding the analysis time intervals, data are evaluated at two different time intervals to address specific challenges: using a 1-second interval is unsuitable, as HR does not adjust instantaneously with changes in body gestures, leading to potential inaccuracies; Conversely, analyzing whole-day data risks smoothing average %HRR values due to discontinuous idling periods, which can obscure high-demand episodes. Therefore, HR data intervals are set to 5 seconds and one hour to ensure a balance between precision and reliability.

Table 3 outlines the results of the t-test across three activity conditions. The p-values of average %HRR comparisons were all greater than 0.05, supporting the null hypothesis that there are no significant differences in %HRR between morning and afternoon periods or between rebar and formwork workers. This indicates that workers' average %HRR values are largely independent of working time, status, or site-specific factors. Figure 10 provides additional insights using hourly data. As shown in Figure 10a, no significant differences are observed between morning and afternoon %HRR averages, suggesting that working time did not influence physical demands. Although the workers engaged in the same tasks, fatigue did not seem to accumulate over time if the workers had sufficient rest (idling work type). Similar results have also been found in Chen and Tserng (2022). However, Figure 10b shows that rebar workers have higher maximum, quartile, and median %HRR values, with several outliers, indicating that rebar work is more physically demanding than formwork tasks.

Using 5-second intervals, as shown in Figure 11, 151,200 data points are analyzed. Figure 11a reveals that afternoon %HRR values are generally higher than morning values, with higher maximum values and more outliers in the afternoon. It can be explained by the fatigue accumulating can be easily noted in shorter time intervals (i.e., 5 seconds) than in longer intervals (i.e., 1 hour). This suggests a greater risk of excessive physical demands later in the day. Figure 11b highlights a significant difference between rebar and formwork workers, with rebar workers' average %HRR exceeding 40% and maximum %HRR

Table 3. t-test results in different situations

Conditions	Different situations	p-value
Average %HRR at different sites in the morning and the afternoon.	Rebar workers	0.4222
	Form workers	0.9901
Average %HRR at the same site in the morning and the afternoon.	Rebar workers at site #1*	0.8979
	Rebar workers at site #2**	0.8268
	Rebar and form workers at site #2	0.6329
Average %HRR at a different site for different work types.	Rebar and form workers	0.7286

Notes: *Site #1: the FoTan construction site; **Site #2: the St. Paul construction site. For the student t-test in this research, the null hypothesis was assumed to be that there is no significant difference between the two conditions listed in the second row of this table. H = 1 means the null hypothesis should be rejected, while when H = 0, the null hypothesis can be accepted.

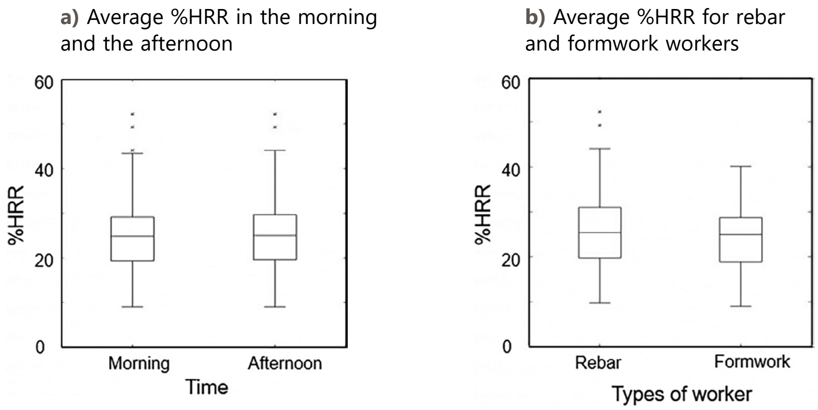

Figure 10. Average %HRR (one-hour as the time interval)

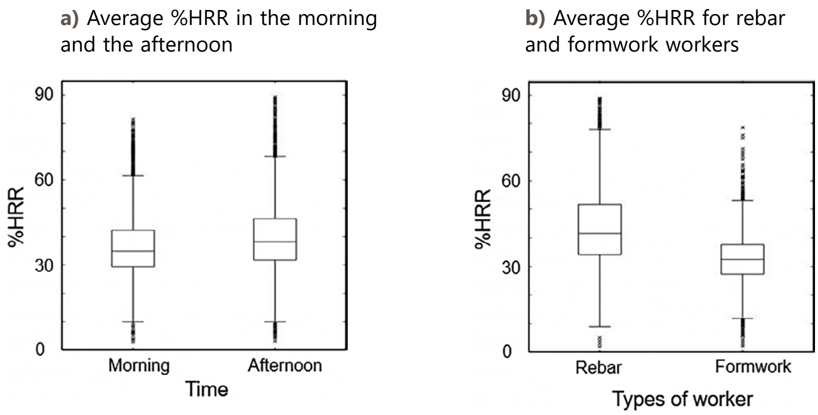

Figure 11. Average %HRR (5-second as the time interval)

values reaching up to 80%. This confirms that rebar work entails considerably higher physical demands than formwork, emphasizing the importance of preventing overloading schedules for rebar workers to safeguard their health and safety.

4. Conclusions

4.1. Academic contributions

This research advances the academic understanding of construction workers' physical demands by proposing a continuous HR data collection via lightweight wearable wristbands. Unlike previous studies that relied on invasive devices or short-term monitoring, this study emphasizes the utility of long-term HR monitoring to analyze workload variations across cyclic and non-cyclic tasks. By bridging the gap in knowledge on continuous physical demand assessment, this research contributes to the broader body of work in occupational health and construction management. The data collected from 10 workers for three weeks showed meaningful variations that can be used to understand work allocation issues (e.g., unbalanced work assignment during a cycle, change of workloads between work cycles) during cyclic construction tasks. In addition, the duration of stationary task type (work without moving) was an essential factor in the %HRR performances of rebar workers. On the contrary, the duration percentage of dynamic task type (work with moving) significantly affect the %HRR values of form workers. It is desirable to mention that some days' daily average %HRR was lower than the 33% threshold, while they also illustrated some demanding moments (over 40% HRR) that lasted for more than half an hour and could damage the workers' health and safety. The analysis revealed no statistically significant differences in average %HRR values between morning and afternoon working periods, nor across different site conditions, when grouped by one-hour intervals. However, rebar workers consistently exhibited higher %HRR values compared to form workers, with more demanding physical work and occasional outliers exceeding 40% %HRR, reaching a maximum of around 80%. Using a finer time interval of 5 seconds, the data showed increased %HRR in the afternoon, indicating higher risks of excessive physical demand during this period. These findings highlight the need for careful workload management, particularly for rebar tasks, to prevent overexertion and improve worker safety.

By systematically integrating continuous HR monitoring with workload analysis, this study not only enhances the methodological rigor of physical demand research but also provides a foundation for future studies to explore advanced strategies for workload optimization. These findings contribute to the academic discourse on sustainable workforce management and health risk mitigation in construction settings. Additionally, this research lays important groundwork for the future application of artificial intelligence (AI) in the field of physical demand monitoring. For example, deep learning algorithms could be developed to automatically recognize workers' task types based on HR patterns, replacing the current reliance on manual classification. Machine learning models could also predict workers' physical demand trends in real time based on %HRR patterns, enabling proactive pre-warning systems to mitigate excessive workloads. Such advancements could enhance both the accuracy and efficiency of workload management in dynamic construction environments. Beyond these applications, the integration of wearable HR devices with AI-based systems could facilitate more precise, individualized workload planning, taking into account real-time health indicators and historical performance data. This approach could lead to adaptive workforce management systems that dynamically adjust task assignments and schedules to optimize productivity while safeguarding worker health. Overall, this study demonstrates the potential of HR-based monitoring as an effective tool for comprehending and optimizing physical demands in the construction industry.

4.2. Practical contributions

Physically demanding information from HR and %HRR data can help the project managers assign the site work without overloading the workers. The on-site data showed meaningful variations in physical demands that imply productivity and task allocation issues at construction sites. Therefore, a potential solution is to assign more skilled tasks to experienced workers. In contrast, inexperienced laborers should be assigned supportive or less skilled work. In this regard, an optimization arrangement can be found to balance production efficiency and workers' safety and health. If the highly intensive workload can be evenly distributed, it may retain more workers; thereby, the labor shortage problem can be potentially alleviated. Further data collection and analysis will be needed, considering demographic differences among construction workers and diverse types of construction tasks. In the long run, this research study can be extended for benchmarking the HR and %HRR by collecting the wristband data as per different trades and activities to understand better between-subject and within-subject variations in physical demands from construction work, suggesting possible intervention strategies such as reasonable arranging for "work-rest schedules" and "work-rest cycles".

The study also links %HRR with specific task types (e.g., stationary and dynamic tasks) and worker roles (e.g., rebar and form workers), offering actionable guidelines for task allocation. For instance, managers can balance physically demanding tasks like rebar work with less intensive activities or schedule breaks during high-intensity periods (e.g., when %HRR exceeds 40% for extended durations) to mitigate risks. Additionally, prolonged HR monitoring uncovers temporal workload patterns, such as increased physical demands during specific periods of the day (e.g., afternoon fatigue), enabling managers to optimize shift schedules and task assignments to prevent overexertion. By doing so, the study aims to guide the development of more effective workload monitoring tools tailored to the construction industry. The non-invasive and cost-effective features of wristband HR monitors make them an attractive solution for practical implementation. Ultimately, this study is expected to provide valuable insights for construction managers and researchers, supporting enhanced workload management, improved safety and health outcomes, and greater efficiency in construction operations.

4.3. Limitations

Despite the valuable insights provided by this research, there are certain limitations that need to be acknowledged. Firstly, the study was conducted with a relatively small sample size of 10 construction workers, which may limit the generalizability of the findings to the broader population of construction workers. Therefore, future research should expand the sample size to include a more diverse range of workers, including different ages, working-experience levels, and work types, to ensure greater representativeness and reliability of the results. Furthermore, the data used in this research was collected from specific construction sites, which may introduce site-specific factors and context that could impact the generalizability of the findings to other construction sites. It is suggested that for further studies, the data from multiple construction sites should be incorporated to improve the external validity of the research. Future research could benefit from incorporating real-time temperature monitoring to more accurately gauge the immediate impacts of environmental conditions on workers' physical demands, thus refining the understanding of how environmental temperature factor influence labor physical performance in construction settings.

Author contributions

Jiayao Wang: Data collection, Formal analysis, Writing – original draft. JoonOh Seo: Methodology, Funding acquisition, Writing – review & editing. Yue Gong: Data collection. Ming-Fung Fransic Siu: Writing – review & editing. Sungjoo Hwang: Methodology. Masood Khan: Writing – review & editing.

Disclosure statement

Authors declare that they do not have any conflicts of interest.

Data availability statement

Data will be made available on request.

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