Technologies for Monitoring Fatigue in Workers: A Human-Centered Approach in the Construction Industry Context

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The article delves into the imperative of adopting a human-centered approach to safeguard the well-being and performance of workers, with a particular focus on civil construction—an industry emblematic of conditions necessitating heightened attention to occupational health and safety. In this context, the study advocates for a systematic review leveraging the optimized BiLi method (Bibliographic and Literary Review Method) to scrutinize the monitoring and diagnosis of fatigue—a pervasive concern impacting worker welfare and productivity. Through meticulous execution of the BiLi method, the research culminated in identifying 10 pertinent articles predominantly elucidating physical fatigue alongside insights into factors contributing to mental fatigue. The study underscores the pivotal role of heart rate monitoring facilitated by wearables in expediting the early detection of fatigue—a pivotal metric for preemptive intervention and mitigation strategies. Furthermore, the review underscores the salience of gauging brain electrical activity and assessing sleep quality as pivotal indicators, offering comprehensive insights into the multifaceted dimensions of fatigue management in occupational settings. By synthesizing these findings, the study contributes substantively to the discourse on worker well-being. It underscores the urgency of adopting proactive measures to mitigate the deleterious effects of fatigue in the workplace, thereby fostering an environment conducive to optimal performance and sustained occupational health.
Keywords: Construction Worker. Fatigue. BiLi Method. Heart Rate.

The human-centered approach has emerged as a pivotal discourse in discussions surrounding the future of manufacturing systems [1]. By fostering collaboration between technology and workers, this approach endeavors to augment technical capabilities while cultivating safer, more inclusive, and healthier working environments. Traditionally, worker behavior within industrial settings has been perceived as static, primarily focusing on physical interactions and often overlooking emotional and physiological factors [2]. However, there is a growing imperative to recognize humans as dynamic elements within industrial systems, particularly in light of the burgeoning concept of Industry 5.0. This paradigm shift signifies a transition toward sustainable societies prioritizing human-centered actions and resilient production systems [3]. Within the construction industry—a sector renowned for its representative role in catalyzing a paradigm shift concerning workers—the challenges are particularly pronounced. Construction workers frequently contend with occupational hazards, enduring high levels of physical and mental strain during task execution, jeopardizing their well-being, safety, and overall performance [4].

Fatigue emerges as a critical concern among workers, characterized by a decline in mental and/or physical performance attributed to cognitive overload, physical exertion, sleep deprivation, or illness. This condition significantly undermines worker safety, health, and performance, ultimately impacting the productivity and quality of their output [5].

Accurately monitoring and diagnosing fatigue, especially within the construction industry, are imperative to cultivating safe, efficient, and productive work environments [6]. This paper underscores the significance of adopting a human-centered approach and prioritizing worker well-being on the shop floor. Through a systematic

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review focusing on monitoring and diagnosing fatigue in construction workers, this study evaluates the technologies and metrics employed to assess workers' performance and health, drawing upon available scientific evidence.

Materials and Methods

The systematic review was conducted using the BiLi method (Bibliographic and Literary Review Method), pioneered by researchers from SENAI CIMATEC. This method offers a streamlined approach to sourcing publications relevant to a specific topic, leveraging appropriate tools for optimal results [7].

Central to the BiLi method are several tools developed within the R programming language, including Bibliometrix, Litsearch, and RevTools [7]. These tools facilitate efficient literature search, bibliometric analysis, and review process management. Additionally, the method recommends employing CmapTools to construct concept maps, aiding in visualizing key themes and relationships within the literature. Furthermore, Mendeley is proposed as a valuable tool for organizing and annotating articles during the reading and analysis phase, enhancing workflow efficiency and data management.

Figure 1 summarizes the BiLi method, which is composed of four stages: (1) naive cycle, (2) optimized cycle, (3) impact cycle, and (4) production cycle. Throughout the steps, the method helps the researcher to filter and select the keywords with the most significant impact, refining the search until reaching the most significant publications for their study.

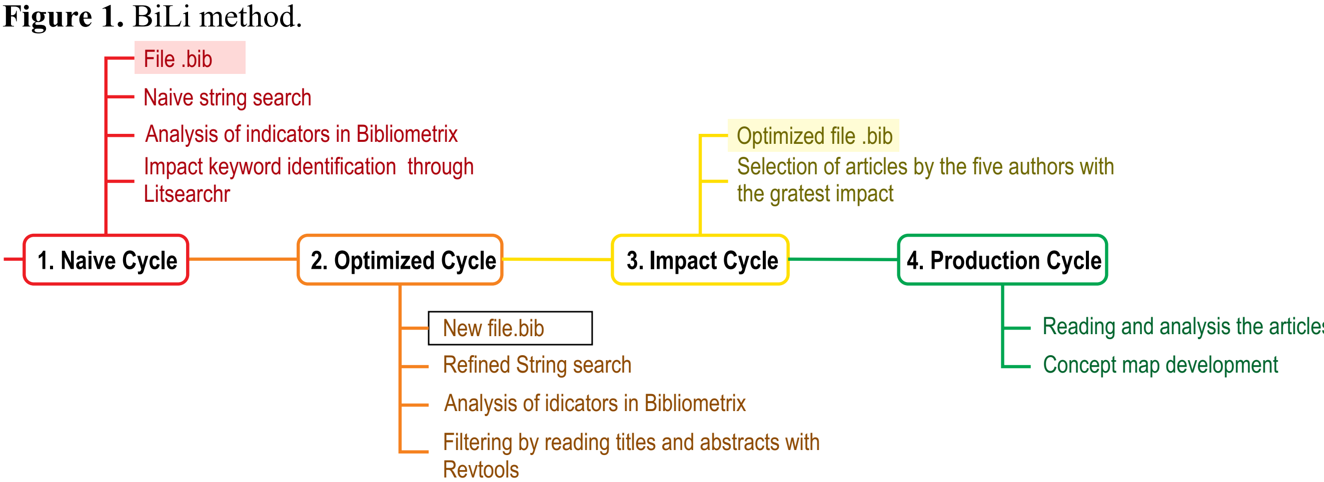
In the naive cycle (Step 1), an initial search was conducted in the Scopus database using broad yet representative keywords: "fatigue" and "construction worker," spanning from 2017 to 2023. This yielded 140 publications. To ensure the relevance and consistency of the results, key indicators such as co-citation networks, annual scientific production, publication history, and word clouds were analyzed using Bibliometrix.

Utilizing the litsearchr tool, an automated metadata analysis of the initial search results was performed to suggest keywords for refining the search string. This led to a new search query: (fatigue AND ("construction worker" OR "construction industry") AND ("heart rate" OR wearable OR sensor)), resulting in 59 publications.

In the optimized cycle (Step 2), the 59 publications were meticulously evaluated and filtered based on graphical indicators in Bibliometrix and by reviewing the titles and abstracts. This rigorous filtering process yielded 30 selected publications.

Moving to the impact cycle (Step 3), the focus shifted to identifying the five most cited authors and their respective articles for further examination. From the pool of 30 publications, 10 highly relevant articles in the study area were identified.

Figure 1. BiLi method.



Source: Adapted from Reis and Vale [7].

As per the method's recommendation, the ranking was extended to include the first seven most cited authors to broaden the scope of analysis. Table 1 presents the authors with the highest impact and their pertinent information.

As a summary of the application of the BiLi method for the chosen systematic search, Figure 2 illustrates the number of publications related to the diagnosis of fatigue in workers in the construction sector for each of the steps.

Results and Discussion

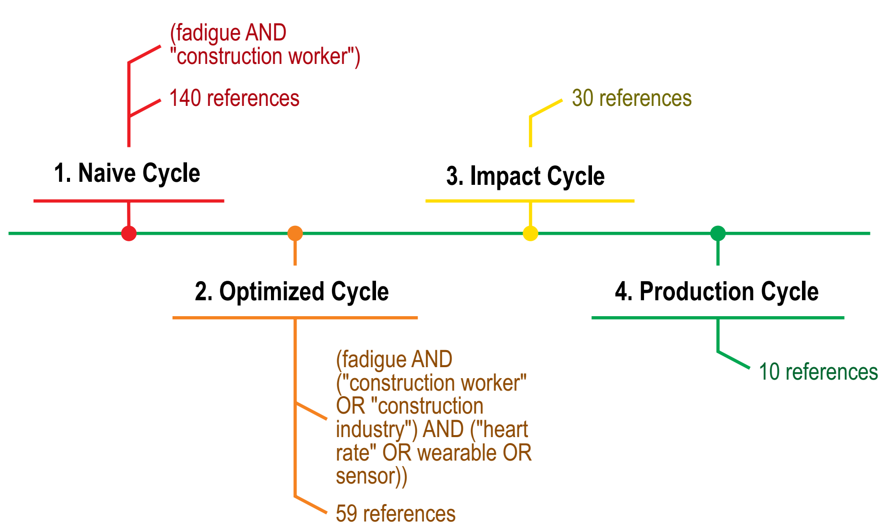
The application of the BiLi method yielded 10 articles, as outlined in Table 2. Notably, the majority of the researchers and publications originated from China. Given the niche nature of the topic, centered on the civil construction segment, the volume of publications obtained was relatively modest compared to more generalized applications. Nonetheless, these findings were deemed adequate to fulfill the defined objectives and offer valuable insights for researchers exploring this specific context further.

Although all the selected articles focus on fatigue as their primary subject, it is essential to recognize the two distinct categories within this condition: physical fatigue and mental fatigue. Mental fatigue pertains to diminished cognitive performance resulting from prolonged periods of intellectual activity [8-10], while physical fatigue arises from strenuous physical exertion.

Table 1. Ranking of top authors listed on Impact Cycle.

Ranking	Author	Citations	Country
1	Heng Li	254	China
2	Ali Ghahramani	180	United States of America
3	Ashrant Aryal	180	United States of America
4	Burcin Becerik-Gerber	180	United States of America
5	Xiaochun Luo	171	China
6	Jue Li	154	China
7	Xuejiao Xing	154	China

Figure 2. Summary of the application of the BILI method.



Notably, only 30% of the chosen articles address research centered on mental fatigue, indicating a concentration of studies on physical conditions and a gap in effective methods for measuring mental fatigue [9].

While some studies investigate physical and mental fatigue separately, a pilot study delved into the effects of physical fatigue in inducing mental fatigue among construction workers. Xing and colleagues' (2020) research utilized cognitive tasks to induce varying degrees of mental fatigue under different levels of physical exertion. The findings demonstrated a significant increase in mental fatigue, suggesting a decline in cognitive performance influenced by heightened physical exertion [10].

Table 2. Top 10 articles obtained on the production cycle.

Authors	Title	Year	Journal	Countries
Aryal A and colleagues	Monitoring fatigue in construction workers using physiological measurements	2017	Automation in Construction	United States of America
Li H and colleagues	Pre-service fatigue screening for construction workers through wearable EEG-based signal spectral analysis	2019	Automation in Construction	China
Yu Y and colleagues	An automatic and non-invasive physical fatigue assessment method for construction workers	2019	Automation in Construction	China
Xing X and colleagues	Effects of physical fatigue on the induction of mental fatigue of construction workers: A pilot study based on a neurophysiological approach	2020	Automation in Construction	China, Australia, United Kingdom
Anwer S and colleagues	Cardiorespiratory and thermoregulatory parameters are good surrogates for measuring physical fatigue during a simulated construction task	2020	International Hounal of Environmental Research an Public Health	
Li J and colleagues	Identification and classification of construction equipment operators' mental fatigue using wearable eye-tracking technology	2020	Automation in Construction	China, Saudi Arabia
Anwer S and colleagues	Test-retest reliability, validity, and responsiveness of a textile-based wearable sensor for real-time assessment of physical fatigue in construction bar-benders	2021	Journal of Building Engineering	China, United Kingdom, Saudi Arabia, Canada.
Anwer S and colleagues	Evaluation of Physiological metrics as a real-time measurement of physical fatigue in construction workers: State-of-the-Art Reviews	2021	Journal of Construction Engineering and Management	China, United Kingdom, Saudi Arabia.
Anwer S and colleagues	Identification and classification of physical fatigue in construction workers using linear and nonlinear heart rate variability measurements	2023	Journal of Construction Engineering and Management	China,United Kingdom, Canada

Various non-intrusive methods for identifying and categorizing physical fatigue has been proposed. Conventional subjective approaches like questionnaires are discouraged due to their inability to provide dynamic and continuous analysis of worker behavior [4]. An innovative approach involves analyzing 3D movement images of workers coupled with biomechanical calculations to estimate joint torques. Algorithms can then discern physical fatigue based on current joint loads and historical data [4].

For assessing perceived physical exertion (PEER), the Borg Scale or Table is commonly employed. This numerical scale ranges from 1, "No exertion," to 10, "Maximal exertion" [6], adapted from the original scale that ranged from 6 to 20 [11,12]. This method gauges sensory perceptions of physical work and individual effort, stress, or distress experienced during physical activity. It has proven reliable for classifying physical fatigue [6,11,12].

The utilization of wearable devices is gaining traction in studies, primarily due to technological advancements and compatibility with the construction environment's demands. These wearables are often washable, reusable, and capable of continuous use over extended periods. They are valuable tools for acquiring real-time physiological data essential for diagnosing physical and mental fatigue. Examples cited in the selected articles include smartwatches [6,12], wearable eye-tracking devices [9], multisensory textiles [13,15], and wearable EEG devices [8]. Heart rate is a predominant metric for diagnosing and predicting fatigue across most studies [6,10-15]. Table 3 provides a comprehensive overview of all cited metrics, their respective references, and the conditions they relate to.

Conclusion

The human-centered approach is paramount for fostering a safe, inclusive, and healthy work environment within the construction industry, particularly concerning the prompt diagnosis and prevention of physical and mental fatigue. The systematic review undertaken in this article has illuminated pertinent studies delving into emerging technologies and metrics for data analysis, alongside strategies for identifying and categorizing fatigue within this domain. Despite advancements, early detection of fatigue remains a formidable challenge for organizations. It is hoped that insights gleaned from these strategies will pave the way for implementing appropriate preventive and interventional measures, thereby mitigating the risks associated with physical and mental exhaustion.

Nevertheless, it is crucial to acknowledge that the review was constrained by the availability

Table 3. Main metrics used for fatigue analysis.

Metric	Reference	Condition
Joint torque	[4]	Physical fatigue
Heart rate	[13,14,12,11,10,15]	Physical and mental fatigue
Electroencephalography (EEG)	[8,11,10]	Mental fatigue
Eye movement	[9]	Mental fatigue
Respiratory rate	[13,12]	Physical fatigue
Skin temperature	[13,12,14,11]	Physical fatigue
Electrodermal activity	[12]	Physical and mental fatigue
Electrical activity of muscles	[14]	Physical fatigue
Sweat	[16]	Physical fatigue

of specialized publications on the subject matter and its application. In future endeavors, we aim to explore a broader spectrum of technologies and metrics employed across diverse industrial sectors, which could also be applicable within the construction context.

Furthermore, there is a pressing need for empirical studies evaluating the efficacy of these interventions in real-world settings. Such endeavors would furnish more robust evidence supporting adopting these approaches within the construction industry.

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