Shehab, L. & Hamzeh, F. (2023). Zooming into workers' psychology and physiology through a lean construction lends. *Proceedings of the 31st Annual Conference of the International Group for Lean Construction (IGLC31),* 92 –103. doi.org/10.24928/2023/0162

ZOOMING INTO WORKERS' PSYCHOLOGY AND PHYSIOLOGY THROUGH A LEAN CONSTRUCTION LENS

Lynn Shehab[1] and Farook Hamzeh [2]

ABSTRACT

Lean construction has long been a constant advocate for perceiving humans as the driving force for most ventures and projects. Among the enablers of investigating the potentials and capabilities of humans are wearable sensors for collecting physiological measurements. Current research on wearable sensors in construction has not yet touched on its applicability or integration with Lean construction. Therefore, this conceptual paper "zooms into the workers' psychology and physiology through a Lean construction lens" by exploring the potentials of employing wearable sensors in Lean construction. It aims to revamp current applications of wearable sensors by providing a comprehensive overview of the current state of wearable sensor technology and its applications in the construction industry. It also discusses how current studies on wearable sensors may be linked to Lean construction principles and how Lean concepts can further enhance and foster their potentials. The paper concludes by presenting the future possibilities and directions of wearable sensors in Lean construction and the impacts they can have on the industry.

KEYWORDS

Wearable sensors, physiology, psychology, measurements, Lean construction.

INTRODUCTION

The seemingly inexorable march of new technologies has rendered some industries negligent of not only the wellbeing of humans, but also their unexploited potentials that got concealed under the new technologies' alluring capabilities. Industry 5.0, a successor to Industry 4.0, has emerged as a supporter for human-centricity, sustainability, and resiliency, which have somehow been overlooked in Industry 4.0 (Leng et al. 2022). A long-standing advocate for human-centricity is Lean management generally, and Lean construction specifically, which bears "people" as a main pillar to its core people-processes-technology triad (Hamzeh et al. 2021). In fact, Lean construction explicitly considers "people" as a main element for the transformation culture that it promotes (Hamzeh et al. 2021). Several studies in the domain of Lean construction have integrated the human touch into their objectives, means, or concepts. However, this touch could pertain to interrelationships, partnerships, physical abilities, cognitive abilities, or more. One approach to this concept is the investigation and analysis of construction workers' physical and cognitive abilities through digital technologies. Barbosa and Costa (2021) identified and analyzed the commonly used methods for measuring, analyzing, and improving construction productivity using digital technologies. Such technologies were

[1] PhD Student, Civil and Environmental Engineering Dept., Hole School of Construction Engineering, University of Alberta, Edmonton, Canada, lshehab@ualberta.ca, https://orcid.org/0000-0002-2708-3550

[2] Associate Professor, Civil and Environmental Engineering Dept., Hole School of Construction Engineering, University of Alberta, Edmonton, Canada, hamzeh@ualberta.ca, https://orcid.org/0000-0002-3986-9534

classified into several categories, including vision-based technologies, sensor-based technologies, and audio-based technologies. Perhaps sensor-based technologies allow for the most intricate exploration of the "people", while still maintaining a non-invasive approach and healthy boundaries. A search for the term "sensor" on IGLC.net only results in seven studies; three of which refer to location sensors such as GPS and RFID technologies, two refer to visual management sensory aids, and one refers to the sensors that a human uses to capture stimuli in an environment as part of a biological mechanism. Only one study by Barbosa and Costa (2021) is related to wearable sensors for physiological measurements. While we might not be there yet in terms of exploiting the potentials of wearable sensors for physiological measurements in Lean construction research, the potentials of revolutionizing this field by intertwining Lean construction and wearable sensors – two independently powerful fields - is promising.

Therefore, this paper conceptualizes on sensor-based technologies in construction by conducting a conceptual walkthrough among extant studies utilizing wearable sensors for physiological measurements in construction and exploring potentials for exploiting Lean principles in this domain. Its objective is to provide research on wearable sensors in construction with a new insight through bridging extant research attempts in this domain to Lean concepts. In addition to embedding Lean concepts into previous studies, Lean theories and the perks that they provide are suggested to further refine future attempts. In this regard, several research questions are put forward and answered: (RQ1) What are wearable sensors and their usages? (RQ2) What studies employed wearable sensors in construction and what were their objectives? (RQ3) Which of the identified studies fall directly under the umbrella of Lean construction? and (RQ4) Which of the identified studies have objectives that fall under Lean construction goals?

This approach is established based on a distinction between two theories: Lean construction and the use of wearable sensors in construction. According to Lukka and Vinnari (2014), there are two types of theories: a domain theory and a method theory. A domain theory is a set of knowledge in an area of study with particular theories and constructs, while a method theory provides new insights into the domain theory to expand or offer an alternative explanation of its concepts. They also note that this distinction between the two theories is rather relative than absolute, and a theory may either be a domain or method theory depending on its role in the paper (Lukka and Vinnari 2014). As the scope of this study is to introduce Lean construction principles and tools as a novel perspective to the research on wearable sensors in construction, wearable sensors in construction are the domain theory that will be analyzed and have its concepts and applications re-evaluated through the method theory, Lean construction.

In the absence of studies utilizing wearable sensors in the context of Lean construction, this study contributes to the body of knowledge by proposing a new perspective to wearable sensor applications and possibly inspiring future research that bridges the two concepts. The paper starts off with a review on Lean construction principles, followed by a definition and classification of wearable sensors for physiological measurements, and a review on studies utilizing wearable sensors in construction. Finally, a bridging attempt between wearable sensors and Lean concepts is carried out. Final conclusions and future research recommendations are eventually proposed.

METHODOLOGY

As this conceptual paper aims to bridge existing theories in two separate contexts, the research methodology followed is theory adaptation. Theory adaptation papers "introduce alternative frames of reference to propose a novel perspective on an extant conceptualization" (Jaakkola 2020). The first step in theory adaptation papers is problematizing a particular concept (domain theory), followed by suggesting some perspective shifts to align the concept to its purpose by drawing from another theory (method theory) that is befitting to guide this shift (Jaakkola 2020).

Having already defined wearable sensors as the domain theory and Lean construction as the method theory of this study, wearable sensors in construction are investigated, and Lean concepts, principles, and tools are suggested to provide a perspective shift to wearable sensor applications. For this purpose, Lean construction principles and tools are discussed to establish a clear basis for the method theory. However, since the objective of this study is to correlate wearable sensors applications in construction to Lean construction, a thorough discussion of Lean construction principles will not be carried out. Instead, a cross-sectional approach will be adopted in an effort to provide a bird's-eye view of Lean construction. Afterwards, wearable sensors in general are introduced by defining and categorizing them. Research on wearable sensors in construction is then reviewed to provide better understanding of this domain theory in the context of construction. To conduct this review, keywords such as "sensor", "physiological measurement", "wearable", "EEG", "heart rate", "EDA", "eye movement", and "breathing rate" were searched for in databases from Google scholar and IGLC.net. Finally, Lean construction principles are used to propose a novel perspective on wearable sensors and their applications, in hopes of stimulating innovative future research for bridging the two theories.

LEAN CONSTRUCTION PRINCIPLES AND TOOLS

A study by Mossman (2018) aimed at answering the question "what is Lean construction?" and compiled results from previous presentations, research papers, and survey responses. One of the definitions described Lean construction as "an application to construction of a management ***philosophy*** defined by the ***ideal*** it pursues, the ***principles*** followed in pursuit of the ideal, and the ***methods*** used to implement the principles." Therefore, perhaps a good start for describing Lean construction without diving into trying to philosophize the ***ideal*** is through the 14 ***principles*** of the Toyota Production System elucidated by Liker (2004). Liker developed the "4P" model that divides the 14 principles into four categories: Philosophy, Process, People and Partners, and Problem Solving as shown in Figure 1. It is worth noting that the 4P model takes the shape of a pyramid, which implies that the foundation of the 14 principles is understanding and embracing the "Philosophy" and that the journey of adopting the principles is rounded off by a successful and perpetual approach of "Problem Solving".

Another famous concept in Lean is its approach towards eliminating three types of waste: Muri (overburden), Mura (unevenness or inconsistency), and Muda (waste) (Hamzeh 2009). Muri entails driving humans (or equipment) beyond their natural thresholds and can lead to safety issues and quality problems. It may be mitigated by ensuring proper process and resource planning (Hamzeh 2009). Mura in workforce (or materials) occurs in response to fluctuations in the process resulting from various factors such as unbalanced loads and highly variable demand (Hamzeh 2009). Muda may be identified as any element that increases cost in the absence of value creation, including workers waiting, unnecessary movement, unused employee talent, "making-do" or starting an activity before it is ready, and so on (Hamzeh 2009).

Moving forward with the elucidated principles, some of the Lean ***methods*** that offer process improvement and waste elimination include Bottleneck Identification and Analysis (BIA), Value Stream Mapping (VSM), Error Proofing (Poka-yoke), and Root Cause Analysis (RCA). In any system, the bottleneck is the subsystem that forms a point of congestion and limits the capacity of any system because of having lower efficiency than other subsystems. This renders the bottleneck the main determinant of the capacity of the system. Bottleneck identification provides the prospect of improving the process after pinpointing its source of impediment, and bottleneck analysis allows improving the system by analyzing the reasons behind the identified low throughput and drawing recommendations for improving its efficiency. An enabler for bottleneck identification and analysis is VSM, where all process steps necessary to transform raw materials into a completed product are visualized as a collection of value adding and nonvalue adding activities linked together (Liker 2004). VSM provides leeway to eliminate bottlenecks and wastes and to increase process flow and value. One way to minimize human errors in any process is "Poka-yoke" or error proofing, which refers to creative measures adopted to prevent errors committed by workers (Liker 2004). Liker (2004) also suggested that the 6th principle of the Toyota Way (standardized work) is a poka-yoke measure as it pertains to tailoring and continuously updating the "standard work chart" to incorporate error-proofing measures. Another view could be the learning curve associated with standardized work, which in turn could minimize errors among workers through unconscious execution of repetitive and previously verified procedures. Finally, RCA fosters searching for the root cause of problems rather than the source, as the root cause often lies beyond the source (Liker 2004). Toyota's problem solving process includes perceiving the initial problem, clarifying it, locating the point of cause, performing root cause analysis, implementing countermeasures, evaluating them, and finally standardizing the process (Liker 2004). Root causes for inefficiencies in a process could go beyond equipment or materials, as human factors could play significant roles in this aspect.

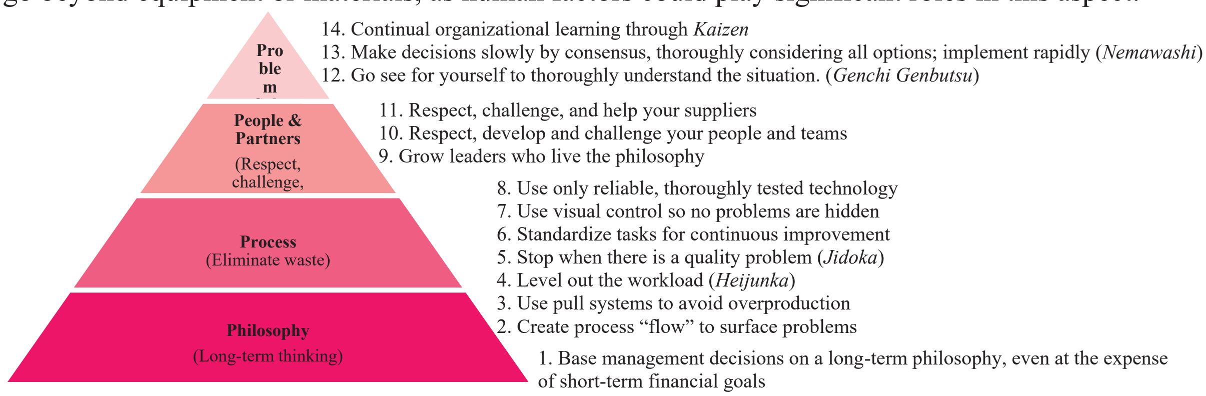

Figure 1: The "4P" Model of the Toyota Way (Liker 2004)

WEARABLE SENSORS FOR PHYSIOLOGICAL MEASUREMENTS

The advancements in wearable technologies have enabled the introduction of real-time wireless sensors for physical and physiological measurements into various industries including healthcare, sports, manufacturing, and construction. Wearable sensors for physiological measurements vary in terms device size, point of application, subject body part, and target measurement. A discussion of the available wearable sensors is carried out to classify the different sensors into categories pertaining to target body parts and target measurements.

Starting with the brain of the human body, electroencephalogram (EEG) devices are used to collect electrical signals created by the activity of neurons near the surface of the brain (Giannakakis et al. 2019). They measure the electrical current fluctuations between the EEG sensor electrode and the skin and amplify these fluctuations before performing any necessary filtering. EEG headsets are available in wired and wireless options and require a consistent electrical connection between the scalp of the subject and the electrodes (Giannakakis et al. 2019). Research has shown that EEG measurements are considered a reliable indicator of mental stress, fatigue, arousal, or psycho-emotional states. Moving to the eyes, eye-tracking sensors are typically used to measure blink counts, eye fixation times and counts, and pupil diameter. Eye blink rate has been analyzed and used by researchers as an indicator of stress in humans, while fixations are the time periods between eye movements when the eye stops at a specific position, and they reflect gazing on an object of interest and can be used to indicate situational awareness or stress. Pupil diameter was proven to indicate processing load and mental effort being exerted by the subject. Eye-tracking has generally been used by researchers in various domains such as risk perception (Hasanzadeh et al. 2017a) and human-computer interaction (HCI).

Heart measurements are arguably some of the most commonly collected measurements, and they include measuring the heart rate, the electrical activity of the heart through electrocardiogram (ECG) devices, and the volumetric change of the blood in the heart through photoplethysmogram (PPG) devices. Heart rate is the number of heart beats per minute, and it is used as an estimate of levels of stress (Giannakakis et al. 2019). Heart rate variability is another measure that is the distribution of the RR interval (interval between consecutive heart beats), and it is considered a valid indicator for stress. ECG, on the other hand, is the signal of the electrical activity manifesting in the heart's contractile activity (Giannakakis et al. 2019) and has been linked to stress in various studies. Finally, PPG is a non-invasive technique used to monitor changes in the blood flow in the cardiovascular system. It is based on illuminating tissues with a specific wavelength and measuring the reflected light (Banerjee et al. 2017). It has also been used to evaluate stress among subjects (Giannakakis et al. 2019).

Another vital component of the human body is the lungs, from which respiration or breathing rate may be measured. Respiration is the rate or volume at which humans exchange air through the lungs. Changes of respiration are observed with changes in the subject's emotional states, where respiration increases with emotional arousal, decreases with relaxation, and undergoes momentary interruption with tense situations (Giannakakis et al. 2019).

When it comes to limbs, movements and muscle electrical activity have been perceived as two significant measures that can help indicate psychological states among subjects. Limb movements are classified into upper and lower body movements, with upper body movements being positively linked to stress levels (Giannakakis et al. 2019), while lower body movements being linked to subjects' safety behavior due to their cyclic nature (Sun et al. 2020). Inertial Measurement Unit (IMU) sensors or motion suits track body motion by being attached to the subject's body. They have been used for various purposes including workers' safety and level of exertion (Ryu et al. 2020). Muscle electrical activity, on the other hand, is measure using electromyogram (EMG) devices. EMG devices measure a muscle's myoelectric activity to assess physical loads acting on a muscle. They are commonly used to evaluate the causes and potential interventions for work-related musculoskeletal disorders (Al-Qaisi et al. 2021).

Finally, the human body's largest organ, i.e., the skin, has also been a target for researchers attempting to identify stress among subjects by measuring the skin temperature and the electrodermal activity (EDA). Generally, variations in the temperature of the skin have been associated with anxiety and stress conditions and are measured at different body parts, such as the finger, face, or arms. EDA is the measurement of the electrical flow through the skin surface and has been extensively linked to stress measurement (Giannakakis et al. 2019).

WEARABLE SENSORS IN CONSTRUCTION RESEARCH

Construction research has been successful in adopting real-time measurement of physiological factors among construction workers using wearable sensors. Such adoptions vary in terms of target measurement, used sensor, human factor, and study objective. Table 1 represents a summary of a review of studies that have adopted this approach in the construction industry. For each study shown in Table 1, the target measurement and the sensor used to measure it are shown, in addition to the human factor that was investigated in the study in terms of measurement, prediction, or detection. Table 2 shows the objectives of the identified studies.

Table 1: Summary of Select Studies Employing Physiological Sensors in Construction

Study	Target Measurement	Sensor	Human Factor
(Al Jassmi et al. 2019)	1a. Respiration rate 1b. Heart rate	1a. Heartrate monitor 1b. Breathing rate	Happiness

	2a. Blood volume pulse 2b. Skin electrical properties 2c. Skin temperature	monitor 2a. PPG 2b. EDA 2c. Thermopile	
(Anwer et al. 2021)	1a. Heartrate 1b. Breathing rate 1c. Skin temperature 2. Skin Temperature 3. Heartrate	1a. Heartrate monitor 1b. Breathing rate monitor 1c. Temperature sensor 2. PPG 3. Heartrate monitor	Fatigue
(Aryal et al. 2017)	1. Changes in the heart rate 2a. Brainwave signals frequencies 2b. Thermoregulatory changes	1. Heart rate monitor 2a. EEG 2b. Thermopile	Fatigue
(Chen et al. 2017)	Brain electrical activity	EEG	Mental workload
(Choi et al. 2019)	Skin temperature	EDA	Risk perception
(Dzeng et al. 2016)	Eye movement	Eye tracking sensor	Hazard identification
(Hasanzadeh et al. 2016)	Eye movement	Eye tracking sensor	Situational awareness
(Hasanzadeh et al. 2017a)	Eye movement	Eye tracking sensor	Hazard identification
(Hasanzadeh et al. 2017b)	Eye movement	Eye tracking sensor	Safety knowledge
(Hwang et al. 2018)	Electrical activity of the brain	EEG	Emotional State
(Jebelli et al. 2018)	Electrical activity of the brain	EEG	Stress
(Jebelli et al. 2019)	1. Heart volumetric change 2. Electrical properties of the skin 3. Skin temperature	1. PPG 2. EDA 3. Thermopile	Stress
(Lee et al. 2021)	1. Heart volumetric change 2. Skin electrical properties 3. Skin temperature	1. PPG 2. EDA 3. Thermopile	Risk perception
(Lee et al. 2017)	1. Heart electrical output 2. Energy expenditure - physical activity levels - sleep quality	1. ECG 2. Accelerometer	Physical responses, health statuses, and safety behaviors
(Plarre et al. 2011)	1a. Heart electrical output 1b. Skin conductance 2. Skin temperature 3. Ambient temperature 4. Body motion data 5. Relative lung volume at rib cage	1. ECG 2. Skin temperature 3. Ambient temperature 4. Accelerometer 5. PPG	Stress
(Ryu et al. 2020)	Whole-body motion data	Accelerometer, gyroscope, magnetometer	Productivity & Safety
(Sun et al. 2020)	Leg movement	Accelerometer, gyroscope, magnetometer	Risk perception
(Umer et al. 2020)	1a. Respiration 1b. Heart electrical output 1c. Skin temperature	1a. Respiration sensor 1b. ECG 1c. Thermopile	Fatigue
(Wang et al. 2019)	Brain electrical activity	EEG	Risk perception
(Wijsman et al. 2011)	1a. Heart electrical output 1b. Respiration 2. Skin conductance 3. Muscle activity	1a. ECG 1b. Respiration sensor 2. EDA 3. EMG	Stress

Table 2: Objectives of Select Studies Using Physiological Sensors in Construction

Study	Objective
(Al Jassmi et al. 2019)	To assess the ability of capturing the effect of construction workers' happiness on their productivity using physiological signals.
(Anwer et al. 2021)	To establish absolute and relative reliability of textile-based wearable sensors to monitor physical fatigue during bar bending and fixing construction tasks.
(Aryal et al. 2017)	To show that physical fatigue in construction workers can be monitored in real time using wearable sensors.
(Chen et al. 2017)	To measure task mental load using EEG and explore the possibility of assessing the cognitive/mental workload of construction tasks through EEG
(Choi et al. 2019)	To show the feasibility of using wearable sensors to understand workers' perceived risk in construction sites continuously.
(Dzeng et al. 2016)	To compare the search patterns of the experienced and novice workers using an eye-tracker by creating a digital building construction site and designing a hazard-identification experiment involving four workplaces featuring obvious and unobvious hazards (e.g., falls, collapses, and electric shocks
(Hasanzadeh et al. 2016)	(1) To identify workers with lower situational awareness (SA) and pinpoint opportunities to provide proactive training and develop guidelines for workers that will reduce human error and accidents; (2) To measure the same workers' SA level after training to determine if their SA improved
(Hasanzadeh et al. 2017a)	To provide a proof of concept that certain eye movement metrics are predictive indicators of human error due to attentional failure and use these findings to identify at-risk construction workers, pinpoint required safety training, measure training effectiveness, and improve future personal protective equipment.
(Hasanzadeh et al. 2017b)	To demonstrate the potential application of eye-tracking technology in studying the attentional allocation of construction workers and to show that eye tracking can be used to improve worker training and preparedness.
(Hwang et al. 2018)	To investigate the feasibility of measuring workers' emotions in the field using a wearable EEG sensor.
(Jebelli et al. 2018)	To improve workers' safety, health, wellbeing, and productivity through the early detection of workers' stress
(Jebelli et al. 2019)	To enhance workers' health, safety, and productivity through early detection of occupational stressors on actual sites.
(Lee et al. 2021)	To provide a new means of automatic, continuous, objective, and non-invasive method for monitoring construction workers' perceived levels of risk
(Lee et al. 2017)	To examine the reliability and usability of wearable sensors for monitoring roofing workers' on-duty and off-duty physiological status and activities.
(Plarre et al. 2011)	To propose, train, and test two models for continuous prediction of stress from physiological measurements captured by unobtrusive, wearable sensors and provide the first classifier of stress that can be readily used in natural environments without pre-calibration
(Ryu et al. 2020)	To provide an in-depth understanding of the linkage between body loads, work experience, techniques, and productivity.
(Sun et al. 2020)	To demonstrate the potential of using wearable sensors to identify workers with personality traits associated with unsafe behavior.
(Umer et al. 2020)	To highlight the advantages of using combined cardiorespiratory and thermoregulatory measures to enhance modelling physical exertion using machine learning algorithms.
(Wang et al. 2019)	To propose a new hybrid kinematic-EEG data type and adopt wavelet packet decomposition to compute the vigilance (risk perception) measurement indices with the

	redefined EEG sub-bands.
(Wijsman et al. 2011)	To detect mental stress by measuring physiological signals using a wearable sensor system

WEARABLE SENSORS FROM A LEAN CONSTRUCTION PERSPECTIVE

It is rather evident that all of the mentioned studies do not bear on Lean construction in terms of directly stated objectives or methods. A search for the terms “Lean”, “Kaizen”, “Toyota”. “Value Stream”, “Root Cause”, “Bottleneck”, or “Proofing” gives back zero results. An inspection of the stated objectives and methods also verifies the lack of link between the studies and Lean.

Liker (2004) referred to “Lean Company X” that claimed to be Lean but ended up being in need for radical improvements to attain the “Lean” attribute. On the other hand, a company can foster the same principles that Lean promotes and employ the same methods and techniques for improvement and control as those adopted by Lean but not identify as a “Lean” company. An analogy between the given example and the current situation of research on wearable sensors in construction and their remoteness from Lean may be drawn. Despite not being referred to as studies in the field of Lean construction, all of the mentioned studies hold Lean principles and goals, such as enhancing safety and the wellbeing of workers, improving productivity, and matching the load to the capacity of the workforce. To further reinforce this view, a bridging attempt between the studies and Lean principles and methods is carried out. In this attempt, every Toyota Principle addressed in each of the identified studies is listed. Additionally, each type of waste among the three wastes identified in Lean (Muda-Mura-Muri) that the studies attempt to eliminate is also listed. Finally, for each study, the Lean tool or technique that may complement the study’s objectives is identified.

All of the identified studies mentioned in Table 1 were found to address Toyota’s principles 1, 5, 8, 12, and 14. Principle 1 calls for basing decisions on long-term philosophies, even at the expense of short-term financial goals. As all studies utilize wearable physiological sensors, it is no secret that some financial compromise is expected from organizations that are willing to invest in some wearable sensors or collaborations with other organizations offering services in this area. However, such investments guarantee financial gain from productivity improvements among construction workers, as all studies have successfully proven a direct negative relationship between physical fatigue and productivity. Principle 5 promotes building a culture of stopping to fix problems. By analyzing physiological measurements and deducing productivity and safety performance, organizations are enforcing a culture of direct intervention when workers’ physiological statuses indicate unsatisfactory conditions. This would not only enhance the workers’ safety and wellbeing, but also improve their productivity and the overall project performance. As for principle 8 calling for using reliable technologies that serve the people, all studies employ verified sensors whose primary goal is to serve the mental and physical wellbeing of the workers. Regarding principle 12, it encourages organizations to monitor the process closely and personally, and what better way could this concept be implemented other than by collecting and analyzing the workers’ physiological and psychological statuses to ensure their mental wellbeing and physical safety are maintained? Finally, principle 14 entails maintaining a culture of continuous learning and improvement or “Kaizen”. By “zooming into the minds and bodies of construction workers” which are in daily variation, we would be instilling the belief that continuous monitoring and learning about the workers’ physiological and psychological statuses are essential for improving the performance of the project, leading to a notion of continuous improvement among all organization members.

Studies addressing risk perception based on eye movements touch on principle 7, which promotes using visual controls to unhide all problems in the process. This link is established through the studies' aim to track eye movements to monitor if and how safety hazards are detected by the subjects. By doing so, they are fostering the importance of visual control in detecting and unhiding risks that may face workers while performing their work.

When it comes to how the selected studies attempt to eliminate any of the three wastes through their objectives, Muda, which is any kind of waste in the process including inefficiency in the workers' efforts, may be considered a prevalent target among all studies. Fundamentally, all of the included studies have one common vision: enhancing construction workers' productivity; some achieve this goal by focusing on stress, mental load, or emotional state, while others achieve it by focusing on physical fatigue or risk perception. When it comes to Muri, or overburden, if perceived from a human-oriented lens, it directly signifies physical or mental overload. For example, studies addressing physical exertion or fatigue may be linked to Muri in terms of their approach to matching task physical loads to the workers' physical capacities, from which their study objectives originated. This also applies to studies addressing mental stress, which arise from tasks' mental loads overpowering workers' mental capacities. Finally, Mura, or unevenness, is mainly manifested in studies that also exhibit Muri-elimination approaches. In fact, Muri is often described as overburden resulting from Mura, which further reinforces this concept. Table 3 summarizes the human factors and the sensors that can be used to identify them and maps them with the discussed Lean concepts in order to visualize the embedded links between the two topics.

Table 3: Mapping of Human Factors, Sensors, and Lean Concepts

Human Factor	Sensor	P1	P5	P7	P8	P12	P14	Muda	Muri	Mura
Stress & Mental Workload	PPG – EDA – EEG – ECG – EMG - skin temperature - ambient temperature – accelerometer - respiration sensor	X	X		X	X	X	X	X	X
Safety & Risk perception	EEG - EDA – PPG - accelerometer - thermopile - eye tracking sensor	X	X	X	X	X	X	X		
Fatigue	EEG - ECG – PPG – thermopile - breathing rate monitor -heart rate monitor	X	X		X	X	X	X	X	X
Happiness	PPG – EDA – thermopile - heartrate monitor - breathing rate monitor	X	X		X	X	X	X		

INSIGHTS AND GAPS

So far, means of utilizing wearable sensors for physiological measurements have been analyzed from the perspective of their potential to revolutionize the area of Lean construction by providing valuable insights into workers' physiological and psychological statuses on the jobsite. However, by switching the lens to analyzing how Lean construction can complement research advancements employing wearable sensors, some key areas where more research is needed to optimize wearable sensor applications in construction are identified. For example, the **standardization of physiological measurements** is vital for ensuring the viability of this approach. Currently, there is no standardization of the type of physiological measurements that should be collected or the method of data collection, which can complicate the comparison of the results between studies and drawing meaningful conclusions. As a major promoter for standardization, Lean construction can help address this limitation by providing guidelines for the measurement and collection processes. In fact, in the discussion of the 6th Toyota principle, Liker (2004) states that "today's standardization is the foundation on which tomorrow's improvement will be built". By standardizing (1) the set of sensors to be used collectively and (2) the method of data collection based on verified studies and analyses, a reliable standard for similar studies adopting this approach can be developed. Another concern is the **integration of wearable sensors into construction workflows**, such as how to minimize disruption to work processes, how to manage the data collected, and how to ensure that the sensors are used consistently and effectively. Many studies in Lean construction have addressed measuring and optimizing workflow in terms of value, labor movement, and design. Such approaches may be adopted to tackle this limitation in the integration process of wearable sensors with Lean construction. Above all, **ethical and humane considerations** such as sustaining the human touch, privacy, and the use of the data for performance management represent additional concerns. With Lean construction's notion towards a human-centric approach in construction 4.0 technologies, unconscious consumption of technological advancements that may backfire and corrupt the construction industry is resisted (Noueihed and Hamzeh 2022). Attempts to demarcate the expansion of technology and its uses in construction are constantly being evoked within the Lean construction community, which can address the concerns around disregarding the ethical aspect of employing wearable sensors in the industry.

CONCLUSION

Most studies using wearable sensors in construction identified their objectives and means from a general productivity or safety standpoint. However, further meta-analysis brings uncovered relationships between these studies and Lean construction to light. This study relates wearable sensors in construction to Lean principles as an initiative to bring about innovative research approaches in this domain. Upon exploring some Lean concepts such as Toyota's 14 principles and the three types of waste, evident links between them and the objectives of existing studies on wearable sensors can be drawn. Results showed that all of the identified studies specified objectives that directly pertain to five of Toyota's principles, while some studies specified objectives that pertain to one additional Toyota principle. Additionally, Muda was a common target among all identified studies to be eliminated, while Muri and Mura were a common target among those pertaining to mental and physical workloads. This conclusion addresses this study's fourth research question as to which of the identified studies have objectives that fall under Lean construction goals. From a different standpoint, a brief analysis on how Lean construction can help foster the utilization of wearable sensors in construction is presented.

This study sets a cornerstone for future research that could use the advancements provided by wearable sensors and put them into use from a Lean construction perspective. Future research could develop conceptual models or frameworks for the use of wearable sensors in a Lean context by systematically specifying steps and measures to be applied for successful implementations. Future studies could also highlight the challenges and opportunities that come with the implementation of wearable sensors in Lean construction, including issues of data privacy, accuracy, and compatibility. Furthermore, from an opposite perspective, wearable sensors can help enhance Lean construction research approach by providing real-time data, improving worker safety and productivity, and reducing waste and errors. Further analysis on this subject may be conducted to reinforce the built connection between the two topics.

REFERENCES

Al-Qaisi, S. K., A. Saba, and I. Alameddine. 2021. "Evaluation of recommended maximum voluntary contraction exercises for back muscles commonly investigated in ergonomics." *Theoretical Issues in Ergonomics Science*, 22 (3): 261–273. https://doi.org/10.1080/1463922X.2020.1758831.

Anwer, S., H. Li, M. F. Antwi-Afari, W. Umer, I. Mehmood, M. Al-Hussein, and A. Y. L. Wong. 2021. "Test-retest reliability, validity, and responsiveness of a textile-based wearable sensor for real-time assessment of physical fatigue in construction bar-benders." *Journal of Building Engineering*, 44: 103348. Elsevier Ltd.

https://doi.org/10.1016/j.jobe.2021.103348.
Aryal, A., A. Ghahramani, and B. Becerik-Gerber. 2017. "Monitoring fatigue in construction workers using physiological measurements." *Automation in Construction*, 82: 154–165. Elsevier B.V. https://doi.org/10.1016/j.autcon.2017.03.003.
Banerjee, S., R. Bailón, J. Lazáro, V. Marozas, P. Laguna, and E. Gil. 2017. "A two step Gaussian modelling to assess ppg morphological variability induced by psychological stress." *Computing in Cardiology*, 1–4.
Barbosa, A. S. da, and D. B. Costa. 2021. "Productivity Monitoring of Construction Activities Using Digital Technologies: a Literature Review." *29th Annual Conference of the International Group for Lean Construction*, 707–716. Lima, Peru.
Chen, J., J. E. Taylor, and S. Comu. 2017. "Assessing Task Mental Workload in Construction Projects: A Novel Electroencephalography Approach." *Journal of Construction Engineering and Management*, 143 (8): 1–13. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001345.
Choi, B., H. Jebelli, and S. H. Lee. 2019. "Feasibility analysis of electrodermal activity (EDA) acquired from wearable sensors to assess construction workers' perceived risk." *Safety Science*, 115: 110–120. Elsevier. https://doi.org/10.1016/j.ssci.2019.01.022.
Dzeng, R. J., C. T. Lin, and Y. C. Fang. 2016. "Using eye-tracker to compare search patterns between experienced and novice workers for site hazard identification." *Safety Science*, 82: 56–67. Elsevier Ltd. https://doi.org/10.1016/j.ssci.2015.08.008.
Giannakakis, G., D. Grigoriadis, K. Giannakaki, A. Roniotis, and M. Tsiknakis. 2019. "Review on psychological stress detection using biosignals." *IEEE Transactions on Affective Computing*, 13 (1): 440–460. https://doi.org/10.1109/TAFFC.2019.2927337.
Hamzeh, F. 2009. "Improving Construction Workflow- The Role of Production Planning and Control." Doctoral Dissertation, UC Berkeley.
Hamzeh, F., V. A. González, L. F. Alarcon, and S. Khalife. 2021. "Lean Construction 4.0: Exploring the Challenges of Development in the AEC Industry." *Proc. of the 29th Annual Conference of the International Group for Lean Construction 2021*, 248–283. https://doi.org/10.24928/2021/0181.
Hasanzadeh, S., B. Esmaeili, and M. D. Dodd. 2016. "Measuring Construction Workers' Real-Time Situation Awareness Using Mobile Eye-Tracking." *Construction Research Congress*, 2894–2904.
Hasanzadeh, S., B. Esmaeili, and M. D. Dodd. 2017a. "Impact of Construction Workers' Hazard Identification Skills on Their Visual Attention." *Journal of Construction Engineering and Management*, 143 (10): 04017070. https://doi.org/10.1061/(asce)co.1943-7862.0001373.
Hasanzadeh, S., B. Esmaeili, and M. D. Dodd. 2017b. "Measuring the Impacts of Safety Knowledge on Construction Workers' Attentional Allocation and Hazard Detection Using Remote Eye-Tracking Technology." *Journal of Management in Engineering*, 33 (5): 04017024. https://doi.org/10.1061/(asce)me.1943-5479.0000526.
Hwang, S., H. Jebelli, B. Choi, M. Choi, and S. Lee. 2018. "Measuring Workers' Emotional State during Construction Tasks Using Wearable EEG." *Journal of Construction Engineering and Management*, 144 (7): 1–13. https://doi.org/10.1061/(asce)co.1943-7862.0001506.
Jaakkola, E. 2020. "Designing conceptual articles: four approaches." *AMS Review*, 10 (1–2): 18–26. AMS Review. https://doi.org/10.1007/s13162-020-00161-0.
Al Jassmi, H., S. Ahmed, B. Philip, F. Al Mughairbi, and M. Al Ahmad. 2019. "E-happiness physiological indicators of construction workers' productivity: A machine learning approach." *Journal of Asian Architecture and Building Engineering*, 18 (6): 517–526. Taylor & Francis. https://doi.org/10.1080/13467581.2019.1687090.

Jebelli, H., B. Choi, and S. Lee. 2019. "Application of Wearable Biosensors to Construction Sites. I: Assessing Workers' Stress." *Journal of Construction Engineering and Management*, 145 (12): 04019079. https://doi.org/10.1061/(asce)co.1943-7862.0001729.

Jebelli, H., S. Hwang, and S. H. Lee. 2018. "EEG-based workers' stress recognition at construction sites." *Automation in Construction*, 93 (January): 315–324. Elsevier. https://doi.org/10.1016/j.autcon.2018.05.027.

Lee, B. G., B. Choi, H. Jebelli, and S. H. Lee. 2021. "Assessment of construction workers' perceived risk using physiological data from wearable sensors: A machine learning approach." *Journal of Building Engineering*, 42: 102824. Elsevier Ltd. https://doi.org/10.1016/j.jobe.2021.102824.

Lee, W., K. Y. Lin, E. Seto, and G. C. Migliaccio. 2017. "Wearable sensors for monitoring on-duty and off-duty worker physiological status and activities in construction." *Automation in Construction*, 83: 341–353. Elsevier. https://doi.org/10.1016/j.autcon.2017.06.012.

Leng, J., W. Sha, B. Wang, P. Zheng, C. Zhuang, Q. Liu, T. Wuest, D. Mourtzis, and L. Wang. 2022. "Industry 5.0: Prospect and retrospect." *Journal of Manufacturing Systems*, 65: 279–295. Elsevier Ltd. https://doi.org/10.1016/j.jmsy.2022.09.017.

Liker, J. K. 2004. *The Toyota Way - 14 Management Principles from the World's Greatest Manufacturer*. McGraw-Hill, NY.

Lukka, K., and E. Vinnari. 2014. "Domain theory and method theory in management accounting research." *Accounting, Auditing and Accountability Journal*, 27 (8): 1308–1338. https://doi.org/10.1108/AAAJ-03-2013-1265.

Mossman, A. 2018. "What is lean construction: Another look - 2018." *Proceedings of the 26th Annual Conference of the International Group for Lean Constructio*, 1240–1250.

Noueihed, K., and F. Hamzeh. 2022. "Envisioning a Human Centric Approach to C4 . 0 Technologies." *Lean Construction Journal*, 156–170.

Plarre, K., A. Raij, S. M. Hossain, A. A. Ali, M. Nakajima, M. Al'Absi, E. Ertin, T. Kamarck, S. Kumar, M. Scott, D. Siewiorek, A. Smailagic, and L. E. Wittmers. 2011. "Continuous inference of psychological stress from sensory measurements collected in the natural environment." *Proceedings of the 10th ACM/IEEE International Conference on Information Processing in Sensor Networks, IPSN'11*, 97–108. IEEE.

Ryu, J., A. Alwasel, C. T. Haas, and E. Abdel-Rahman. 2020. "Analysis of Relationships between Body Load and Training, Work Methods, and Work Rate: Overcoming the Novice Mason's Risk Hump." *Journal of Construction Engineering and Management*, 146 (8): 04020097. https://doi.org/10.1061/(asce)co.1943-7862.0001889.

Sun, C., S. Ahn, and C. R. Ahn. 2020. "Identifying Workers' Safety Behavior–Related Personality by Sensing." *Journal of Construction Engineering and Management*, 146 (7): 04020078. https://doi.org/10.1061/(asce)co.1943-7862.0001863.

Umer, W., H. Li, Y. Yantao, M. F. Antwi-Afari, S. Anwer, and X. Luo. 2020. "Physical exertion modeling for construction tasks using combined cardiorespiratory and thermoregulatory measures." *Automation in Construction*, 112: 103079. Elsevier. https://doi.org/10.1016/j.autcon.2020.103079.

Wang, D., H. Li, and J. Chen. 2019. "Detecting and measuring construction workers' vigilance through hybrid kinematic-EEG signals." *Automation in Construction*, 100 (July 2018): 11–23. Elsevier. https://doi.org/10.1016/j.autcon.2018.12.018.

Wijsman, J., B. Grundlehner, H. Liu, H. Hermens, and J. Penders. 2011. "Towards mental stress detection using wearable physiological sensors." *Proc. Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 1798–1801.