

Article

Fatigue Monitoring Technologies in Construction: How Professionals Perceive, Trust, and Prefer Subjective, Objective, and Hybrid Approaches

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Abstract

Fatigue remains a persistent contributor to safety incidents in construction; however, limited research has examined how industry professionals perceive and prioritize fatigue monitoring approaches in real-world settings, particularly within the context of increasing digitization and data-driven safety management. To address this gap, this study conducted an exploratory survey of 103 construction professionals, including workers, supervisors, safety personnel, and project managers, to assess their familiarity with subjective, objective, and hybrid fatigue monitoring methods, along with their implementation preferences and perceived challenges. Descriptive statistical analysis and qualitative interpretation were used to evaluate familiarity levels and method preferences. The results indicate that subjective approaches, such as self-assessments and rating-based check-ins, are more widely recognized (mean $\approx 2.1/5$), while awareness of objective, sensor-based systems remains lower ($\approx 1.5/5$). Despite this disparity, approximately 38% of respondents preferred hybrid approaches that integrate subjective inputs with wearable or physiological data, and a similar proportion perceived these approaches as the most reliable for operational decision-making. Additionally, more than 85% of participants indicated that fatigue monitoring could moderately to significantly improve job-site safety. These findings suggest that successful adoption depends on usability, user acceptance, and the effective integration of digital monitoring tools into construction workflows.

Keywords: fatigue monitoring; construction safety; wearable sensing; hybrid monitoring systems; industry readiness; construction digitization



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1. Introduction

Effective fatigue monitoring is a critical dimension of safety management in construction, yet its systematic adoption across the industry remains limited. Despite growing technological capabilities, little is known about how construction professionals perceive, evaluate, and prefer fatigue monitoring approaches in real-world settings. The construction

industry remains one of the most hazardous occupational sectors, consistently reporting disproportionately high rates of injuries and fatalities [1]. Globally, construction workers account for up to 40% of work-related deaths despite representing only a small share of the labor force [2]. In the United States, they comprised 19.5% of all job-related fatalities in 2022 while making up just 7.5% of the workforce [3]. This persistent imbalance underscores the need for more targeted and effective safety interventions. While traditional safety efforts have emphasized physical protections, recent research highlights the role of worker well-being and cognitive performance—particularly fatigue—in shaping safety outcomes [3].

Fatigue is a multidimensional condition encompassing physical, mental, and emotional components [4,5]. In construction, physical fatigue often results from strenuous labor and awkward postures [6], mental fatigue arises from cognitively demanding tasks that impair attention and decision-making [7], and emotional fatigue develops through sustained exposure to high-pressure work environments. Collectively, these fatigue dimensions degrade performance by slowing reaction times, increasing error rates, and contributing to stress and burnout [8], making fatigue a significant contributor to unsafe behaviors and incidents on construction sites.

Managing fatigue in construction is particularly challenging due to dynamic site conditions, variable schedules, and exposure to extreme environmental demands [9]. Unlike more regulated industries such as transportation, construction lacks standardized fatigue management protocols or widely adopted monitoring frameworks [10]. As a result, project teams must independently decide whether and how to implement fatigue monitoring practices, often without evidence-based criteria. Fatigue can be assessed using subjective tools or objective technologies, each with distinct advantages and limitations. Subjective methods, such as questionnaires and rating scales, are inexpensive and easy to administer but are vulnerable to self-report bias and underestimation [11–13]. Objective approaches, including wearable sensors and physiological monitoring, offer quantifiable indicators but raise concerns related to cost, comfort, and intrusiveness [14]. Hybrid systems that combine subjective and objective data have demonstrated improved accuracy and more actionable insights [15,16]; however, their practical adoption remains uneven.

Despite growing interest in fatigue management, limited empirical evidence exists on how construction workers, supervisors, and project managers perceive and evaluate these monitoring approaches. Industry acceptance, familiarity with emerging technologies, perceived intrusiveness, and preferred deployment strategies are rarely examined, even though these human-centered factors strongly influence implementation success. To address this gap, this study presents an exploratory descriptive survey of 103 construction professionals to document their familiarity with and preferences for perceived reliability of subjective, objective, and hybrid fatigue monitoring strategies. Rather than assessing the technical accuracy of specific devices, the study emphasizes practitioner perceptions and deployment considerations that shape managerial decision-making. By capturing perspectives across multiple occupational roles, this work provides foundational evidence to support the development of practical, acceptable, and context-sensitive fatigue monitoring frameworks for construction safety management. Specifically, this study is guided by four research questions: (1) What is the extent of construction professionals' prior exposure to fatigue monitoring practices? (2) How do professionals evaluate different monitoring approaches in terms of comfort and perceived reliability? (3) What is the degree of familiarity with subjective and objective fatigue assessment methods across occupational roles? (4) What deployment strategies and operational responses do practitioners prefer, and how do they perceive the safety impact of fatigue monitoring?

2. Literature Review

2.1. Definition of Fatigue

Construction worker fatigue is commonly characterized by reduced efficiency or a subjective unwillingness to exert effort resulting from physical or mental exhaustion. From a physiological perspective, physical fatigue is defined as a decline in maximal force-generating capacity during muscular activity, often referred to as muscle fatigue [17]. More broadly, fatigue has been conceptualized as a biological drive for restorative rest following prolonged wakefulness, reflecting impaired physical and cognitive functioning [18].

2.2. Categories of Fatigue

Fatigue is generally classified into physical and mental types, which differ in origin and manifestation [19]. Physical fatigue results from prolonged or intense activity that exceeds the body's metabolic capacity, leading to muscular exhaustion and reduced contraction rates [3]. Mental fatigue arises from sustained cognitive demands and is associated with reduced attention, slower responsiveness, low mood, and irritability [19]. In construction, mental fatigue has been identified as a contributing factor to equipment-related accidents due to impaired hazard recognition and decision-making [20]. While the physical–mental classification is standard in the fatigue literature, it is important to acknowledge a third dimension referenced in the Introduction: emotional fatigue, which develops through sustained exposure to high-pressure or interpersonally demanding work environments [4,5]. Although the broader literature on occupational fatigue commonly incorporates this emotional component, the background sections of this study concentrate on physical and mental fatigue types, which are most directly measurable in construction contexts and most commonly targeted by existing monitoring technologies.

2.3. Causes of Fatigue

Fatigue in construction is influenced by a combination of environmental, behavioral, and occupational factors. Harsh working conditions such as extreme temperatures, noise, and vibration exacerbate physical exhaustion [21]. Sleep deprivation and poor sleep quality, often linked to irregular schedules or stress, reduce recovery capacity [22], while rotating or night shifts disrupt circadian rhythms [23]. Psychological stressors, including high job demands, tight deadlines, and job insecurity, further contribute to fatigue [24]. Additional contributors include nutritional deficiencies, dehydration [25], poor ergonomic design [26], and long commuting times that limit rest opportunities [27]. Figure 1 summarizes the key causes and consequences of construction worker fatigue.

2.4. Consequences of Fatigue

Fatigue has wide-ranging consequences affecting worker safety, productivity, organizational stability, and public welfare. Physical and mental fatigue often interact, amplifying risks on construction sites [28]. This includes increased accident rates [29–31], productivity losses and project delays [32–35], and higher turnover that exacerbates labor shortages [36–38]. Fatigue also undermines team cohesion and morale [39,40], increases environmental and public safety risks [41,42], contributes to psychological strain and burnout [43,44], limits the capacity for skill development and innovation [45,46], and exposes organizations to legal and regulatory risks [47–49].

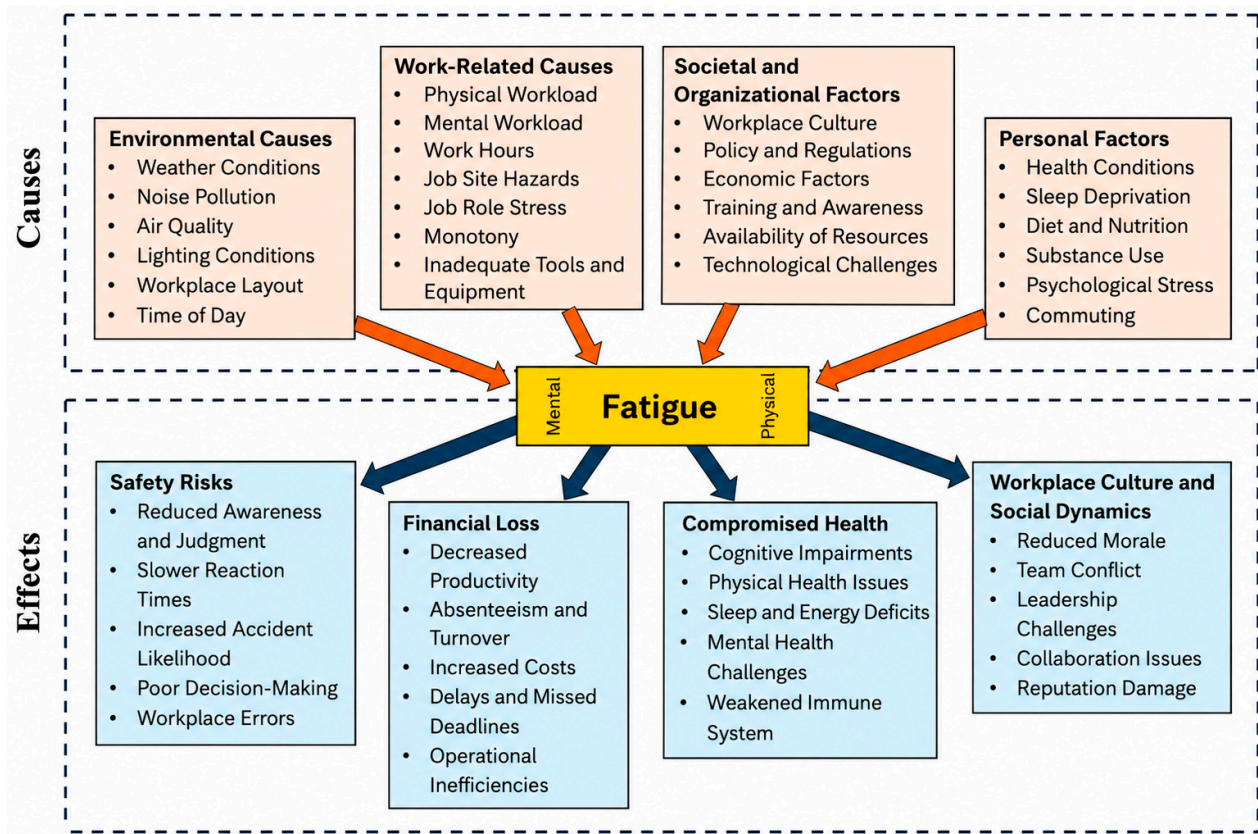


Figure 1. Key causes and consequences of construction worker fatigue.

2.5. Fatigue Measurement Techniques

Construction worker fatigue is commonly assessed using subjective or objective methods. Subjective approaches rely on self-reported perceptions collected through questionnaires, rating scales, or daily logs, whereas objective methods use quantifiable physiological or biomechanical indicators such as heart rate, skin temperature, posture, or motion patterns. Each approach offers distinct advantages and limitations when applied in dynamic construction environments.

Subjective fatigue reflects workers' self-assessed perceptions of tiredness, exhaustion, or reduced energy and is typically measured using questionnaires or rating scales [50]. These tools are widely used due to their low cost, ease of administration, and suitability for field conditions [51,52]. Common instruments assess sleepiness, fatigue severity, sleep quality, workload, and daily energy fluctuations [53–61]. These measures provide insight into how fatigue influences cognitive and physical performance and support the early identification of at-risk individuals [62]. However, their effectiveness depends on workers' awareness, honesty, and willingness to report fatigue, and field studies show that prediction models based on self-reports often achieve only low to medium accuracy [63]. Performance-based assessments further demonstrate that higher fatigue levels are associated with increased error rates [29], underscoring the limitations of relying solely on subjective data.

Objective fatigue detection methods generate quantifiable data independent of self-report by using standardized physiological and behavioral indicators [64]. Common technologies include EEG (Electroencephalography) and ECG (Electrocardiography) monitoring [65,66], actigraphy and motion analysis [12,67], ocular measures such as pupillometry and eye-tracking [68,69], and wearable sensors measuring posture, skin temperature, and perspiration [70]. Additional approaches assess reaction time [71], voice characteristics [72], and blood oxygen saturation [73], while emerging smart helmet systems integrate multiple sensors for real-time fatigue detection [74]. Advances in mobile and wearable technologies

have enabled fatigue prediction accuracies exceeding 75% in some applications [75,76]. Nevertheless, objective methods often require substantial financial investment, technical expertise, and ongoing maintenance and may reduce worker compliance due to discomfort or intrusiveness [77,78]. Table 1 summarizes these objective fatigue detection methods by primary measurement focus.

Table 1. Objective methods of fatigue detection for construction workers.

Category	Tools	Description
Brain Activity	EEG (Electroencephalography)	Monitors brainwave patterns to assess alertness and detect mental fatigue levels [66].
Cardiovascular	ECG (Electrocardiography)	Tracks heart rate variability to identify physical and mental fatigue [65].
Cardiovascular	Heart Rate Monitors	Measure pulse rate and heart rate variability; high variability can indicate physical fatigue [79].
Movement and Sleep Patterns	Actigraphy Devices	Worn as wristbands to record movement and sleep–wake cycles, assessing rest and activity [67].
Movement and Sleep Patterns	Accelerometers	Detect body movements and physical activity levels, indirectly reflecting physical fatigue. [80]
Eye and Pupil Activity	Pupillometry	Measures pupil dilation and response; changes indicate mental fatigue [81].
Eye and Pupil Activity	Eye-Tracking Devices	Track blink rates, saccades, and eye movements, which alter with fatigue [68].
Response Time	Reaction Time Testing	Assesses speed of response to stimuli; slower reaction times are signs of fatigue [71].
Wearable Physiological Sensors	Wearable Sensors	Tracks skin temperature, perspiration, and posture, which correlate with fatigue levels [82].
Wearable Physiological Sensors	Smart Helmets	Equipped with sensors to monitor brain activity, heart rate, and other parameters for real-time fatigue detection [74].
Voice Analysis	Voice Analysis Software Tools	Analyzes voice tone, pitch, and rhythm; changes may reflect fatigue [83].
Blood Oxygen Monitoring	SpO ₂ Monitors	Measure blood oxygen saturation levels, where lower levels can indicate fatigue onset [73].

Given the limitations of relying on a single approach, hybrid methods that integrate subjective and objective data are increasingly advocated. Combining personal perceptions with continuous physiological monitoring improves fatigue detection accuracy, enables cross-validation between perceived and physiological fatigue, and supports more context-sensitive and tailored interventions [36,42,84–86]. Recent reviews indicate that most construction fatigue research now relies on objective or hybrid methods, with relatively few studies using subjective evaluations alone [87,88]. Table 2 summarizes the advantages and disadvantages of subjective and objective fatigue detection methods reported in the literature.

Table 2. Analytical comparison of subjective and objective fatigue detection methods across key implementation dimensions.

Dimension	Subjective Methods	Objective Methods	Hybrid Methods
Detection Accuracy	Low to moderate; susceptible to self-report bias and underreporting [13,63]	Moderate to high; physiological indicators provide objective, quantifiable data [89,90]	High; cross-validation of subjective and objective signals improves overall accuracy [84,85]
Reliability	Variable; depends on worker honesty, awareness, and consistency of self-assessment [11,13]	Generally high for continuous sensing; sensitive to signal artifacts and equipment quality [91]	Highest; integrates multiple data streams to reduce single-source error [36,86]

Table 2. *Cont.*

Dimension	Subjective Methods	Objective Methods	Hybrid Methods
Intrusiveness	Low; questionnaires and rating scales impose minimal disruption to workflow [50,51]	Moderate to high; wearable devices and physiological sensors can interfere with PPE and mobility [77,78]	Moderate; depends on sensor configuration, but lower than full objective suites alone [15,16]
Cost	Low; minimal equipment required; scalable to large workforces at low unit cost [52]	High; hardware procurement, maintenance, calibration, and IT infrastructure add substantial cost [77,92]	Moderate to high; cost varies by sensor type selected for the objective component [84]
Ease of Deployment	High; minimal training required; bilingual and simplified formats suitable for field settings [93,94]	Low to moderate; requires technical expertise, device setup, and ongoing data management [75,76]	Moderate; requires planning for integration, but the subjective component eases onboarding [36,86]
Suitability for Construction	High for routine screening; widely familiar and easily embedded into existing safety workflows [87]	Low to moderate currently; environmental conditions (heat, dust, vibration) affect sensor performance [9,78]	High; recommended approach given practitioner preferences and operational realities identified in this study [15,16]

3. Methodology

3.1. Survey Design and Overview

This study employed an exploratory, cross-sectional, mixed-methods survey design to examine construction professionals' familiarity with and preferences for subjective, objective, and hybrid fatigue detection approaches. An exploratory design was selected to characterize industry perceptions and readiness rather than to test predefined hypotheses or evaluate device accuracy. The methodological framework followed a structured four-step process encompassing instrument development, data collection, quantitative analysis, and qualitative interpretation (Figure 2).

3.2. Survey Instrument Structure

A structured survey instrument was developed to collect both quantitative and qualitative data. The instrument consisted of three sections. The first captured demographic and professional characteristics, including job role, years of experience, and prior exposure to fatigue measurement practices. The second assessed respondents' self-reported familiarity with subjective fatigue detection methods (e.g., questionnaires and observational assessments) and objective methods (e.g., wearable sensors and physiological indicators). Familiarity was rated on a Likert scale ranging from "not familiar at all" to "very familiar", with higher scores indicating greater perceived familiarity. The third section examined method preference, asking respondents to indicate whether they favored subjective, objective, or hybrid fatigue detection approaches and to provide open-ended explanations supporting their selections. In total, the instrument comprised 38 items distributed across the three sections: 6 items in Section 1 (demographics and exposure), 22 items in Section 2 (familiarity ratings across 10 subjective and 10 objective methods, plus 2 hybrid-awareness items), and 10 items in Section 3 (preference selection, deployment questions, and open-ended responses). Representative items included: "How familiar are you with the use of daily fatigue diaries or shift-end logs on construction sites?" (5-point Likert scale, Section 2); "Which fatigue monitoring approach do you consider most comfortable to use during your typical workday?" (multiple choice, Section 3); and "Please briefly explain why you prefer this approach over others." (open-ended, Section 3). The full instrument is available from the corresponding author upon reasonable request.

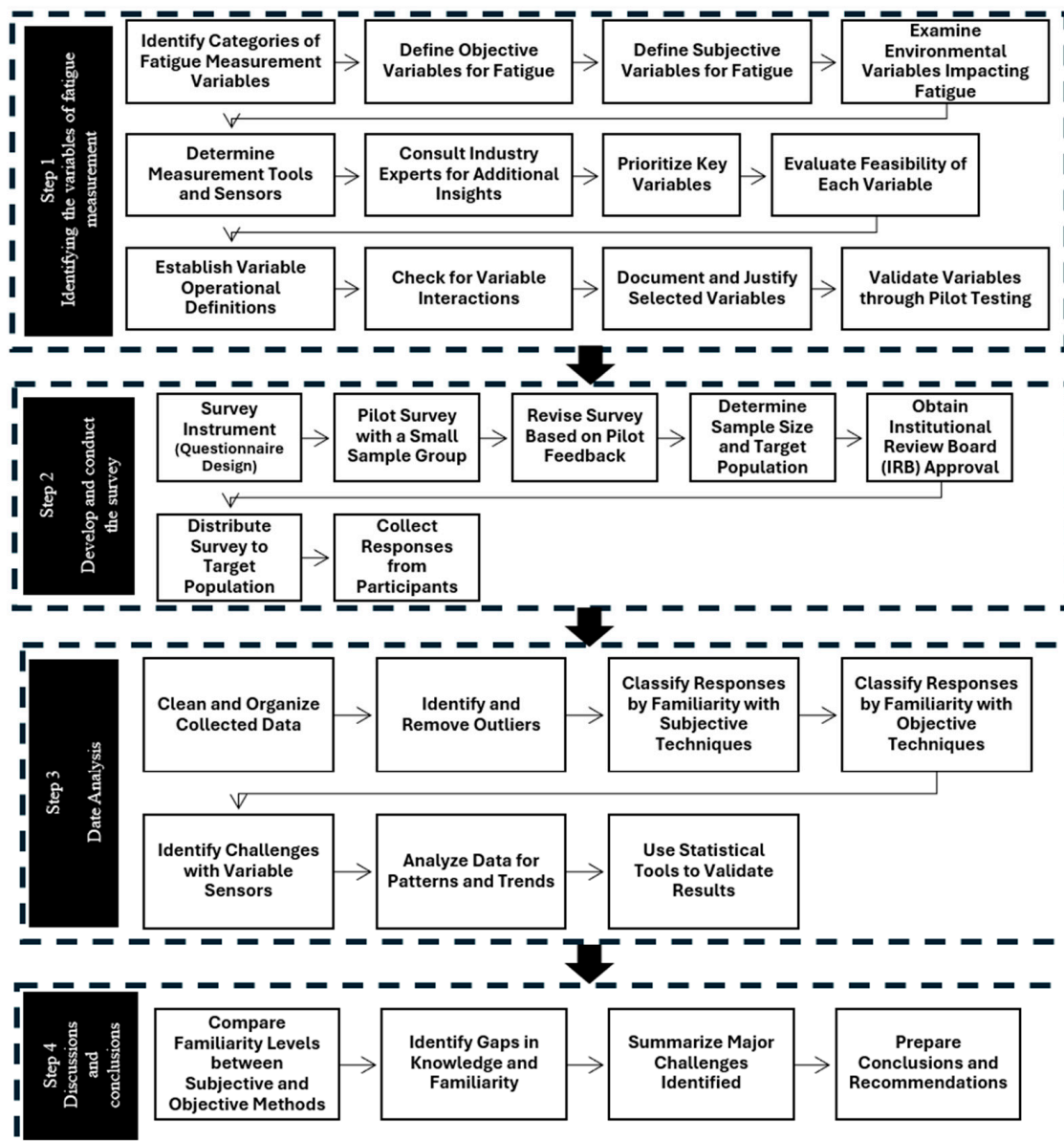


Figure 2. Methodological framework: four-step survey design process (instrument development, data collection, quantitative analysis, and qualitative interpretation).

3.3. Instrument Development, Validation, and Pilot Testing

Survey items were developed based on prior research in construction safety, fatigue management, and human factors. To enhance content validity, the draft instrument was reviewed by a three-member expert panel comprising a construction safety manager, an ergonomics researcher, and an academic specializing in human factors and worker cognition. Expert feedback focused on construct relevance, clarity of terminology, response format suitability, and logical sequencing. Revisions were made accordingly.

A pilot test was conducted with eight construction professionals to assess comprehension, usability, and survey flow. Based on pilot feedback, definitions of subjective and objective fatigue detection were refined, technical terminology was simplified, and instructions were clarified. A Spanish version of the survey was reviewed by a bilingual safety trainer to ensure conceptual equivalence rather than literal translation. Internal consistency across related Likert-scale items was assessed using Cronbach's alpha. Given the exploratory intent and the limited number of items per construct, reliability values were modest but acceptable for identifying practitioner trends and informing subsequent research.

3.4. Sampling Strategy and Participant Recruitment

A purposeful sampling strategy was employed to capture perspectives from construction professionals directly involved in field operations or safety-related decision-making. Surveys were administered across nine active construction projects (six residential and three commercial) to reflect variability in project type, scale, and operational context. Eligibility required direct exposure to job-site conditions or safety oversight responsibilities. Surveys were administered in person during scheduled break periods to minimize work disruption. Trained researchers were present to clarify questions while maintaining neutrality. Participation was voluntary and anonymous. Email addresses were collected only from participants who opted to receive study results. All nine projects were located in the southeastern United States. Project values ranged from approximately \$2 million to \$85 million and spanned both public and private sector clients across six residential and three commercial developments. This geographic and project type diversity was intentional, as construction safety practices, workforce demographics, and technology adoption patterns can vary meaningfully across project scales and organizational contexts. Regarding ethical compliance, this study met IRB exempt-status criteria under 45 CFR 46.104 (anonymous survey research involving adult professionals). Participation was entirely voluntary, no individually identifiable data were collected, and participants were informed of the study's purpose prior to completing the survey. To assess the adequacy of the sample, a post hoc power analysis was conducted using G*Power (version 3.1). Assuming a medium effect size (Cohen's $h = 0.30$), a significance level of $\alpha = 0.05$, and a desired power of 0.80, the minimum required sample size for one-proportion z-tests was calculated to be 88 participants. The obtained sample of $N = 103$ exceeds this threshold, confirming that the sample is sufficient to detect medium-sized effects with adequate statistical power. Additionally, a response rate of 29% (103 of 357 invited) is consistent with norms reported for in-person, field-based construction surveys, supporting the representativeness of the sample within the studied project contexts.

3.5. Data Collection Procedures

Data collection occurred under varied seasonal and workload conditions to reflect realistic job-site fatigue environments. Surveys were interviewer-administered on paper and required approximately 10 min to complete. The use of plain language, bilingual materials, and on-site researcher support minimized misinterpretation and respondent burden. No incentives were provided to avoid coercion, and anonymity was emphasized to reduce social desirability bias.

3.6. Quantitative and Qualitative Data Analysis

Because this study focused on understanding practitioners' familiarity and preferences rather than causal relationships, a combined analytical approach was used. Quantitative data were analyzed using descriptive statistics (means, frequencies, and proportions) to establish baseline trends, while qualitative responses were examined through thematic coding by two researchers to identify key patterns. Together, these methods provide a concise yet meaningful overview of industry perspectives, with qualitative insights enriching the quantitative findings.

3.7. Methodological Scope and Limitations

Although purposeful sampling facilitated access to practitioners with relevant safety responsibilities, the findings may not generalize beyond the project contexts examined. Variations in organizational culture, technology exposure, and regional practices may influence familiarity with fatigue monitoring methods. The reliance on descriptive statistics

limits causal inference but aligns with the exploratory objective of documenting industry readiness and informing future validation and implementation studies.

4. Results

This section reports descriptive and exploratory findings addressing the study objectives: (1) documenting construction professionals' prior exposure to fatigue monitoring, (2) examining preferences regarding the comfort and perceived reliability of monitoring approaches, (3) assessing familiarity with subjective and objective fatigue assessment methods, and (4) identifying preferred deployment strategies, operational responses, and perceived safety impacts.

4.1. Respondent Profile

Of the 357 construction professionals invited to participate, 103 completed the survey, yielding a response rate of 29%. Respondents represented frontline construction workers, site supervisors, safety officers, project managers, and related personnel involved in job-site safety decision-making. Figure 3 shows a Cleveland dot plot of the distribution of respondents based on their role. This distribution demonstrates that the survey captured perspectives across multiple tiers of construction management and oversight, while emphasizing the groups most exposed to daily fatigue challenges. The smaller share of project managers reflects the typical staffing structure of construction projects, where a limited number of project managers oversee larger teams of site supervisors and construction workers.

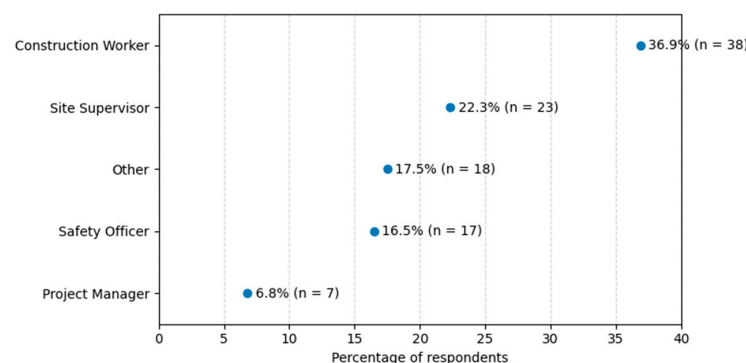


Figure 3. Distribution of respondents by professional role ($N = 103$).

Figure 4 illustrates the distribution of respondents by years of experience in the construction industry. Most respondents reported substantial industry tenure, with 67.96% indicating more than 10 years of experience. This indicates that the sample was heavily weighted toward experienced professionals with over a decade in the industry.

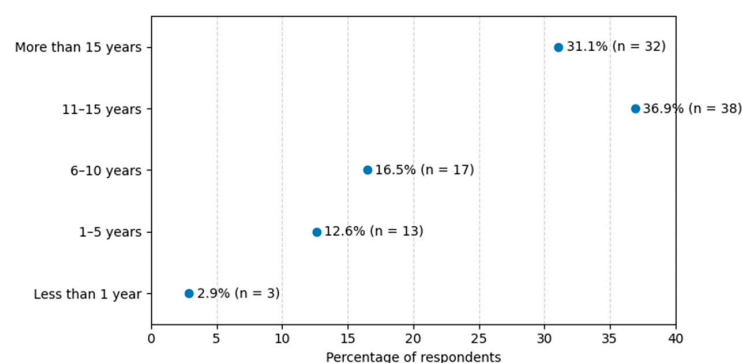


Figure 4. Distribution of respondents by years of construction industry experience ($N = 103$).

4.2. Prior Exposure to Fatigue Monitoring

Respondents were asked to report their prior exposure to fatigue monitoring methods in construction settings. Figure 5 summarizes the distribution of responses across four exposure levels. Dots represent observed proportions, while horizontal lines indicate exact 95% binomial confidence intervals. Percentages are shown with corresponding respondent counts.

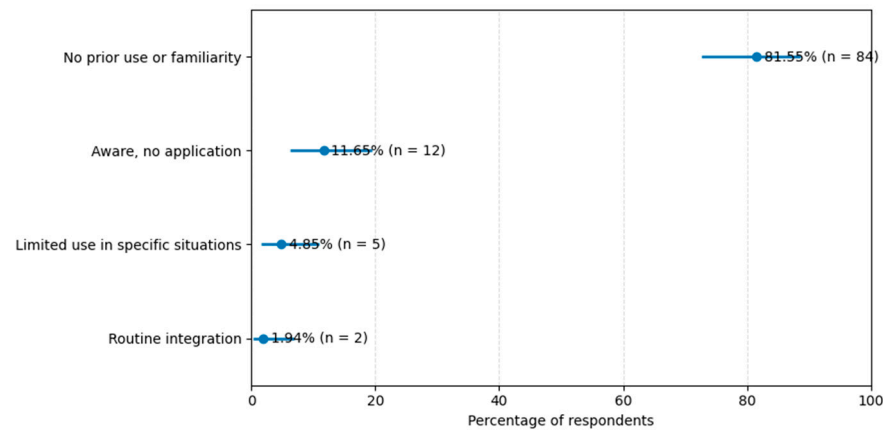


Figure 5. Prior exposure to fatigue monitoring methods among surveyed professionals ($N = 103$).

This distribution reveals a substantial gap between the availability of fatigue monitoring technologies and their practical adoption in the construction sector. The predominance of unfamiliarity suggests that both limited access and lack of awareness remain critical obstacles. These results point to a need for industry-wide efforts not only to raise awareness but also to embed fatigue monitoring into standard safety management practices, thereby shifting its role from a reactive to a proactive measure.

4.3. Comparative Preferences for Fatigue Monitoring Approaches (Comfort- and Trust-Based)

Understanding how construction professionals evaluate different fatigue monitoring approaches provides insight into their acceptance and potential for adoption. Participants were asked to identify the fatigue monitoring approach they considered most comfortable for implementation on construction sites. Figure 6 presents the distribution of comfort-based preferences across the five response categories. Dots represent observed proportions; horizontal lines indicate exact 95% binomial confidence intervals. Confidence intervals were estimated using exact binomial methods to account for variability in category-level sample sizes.

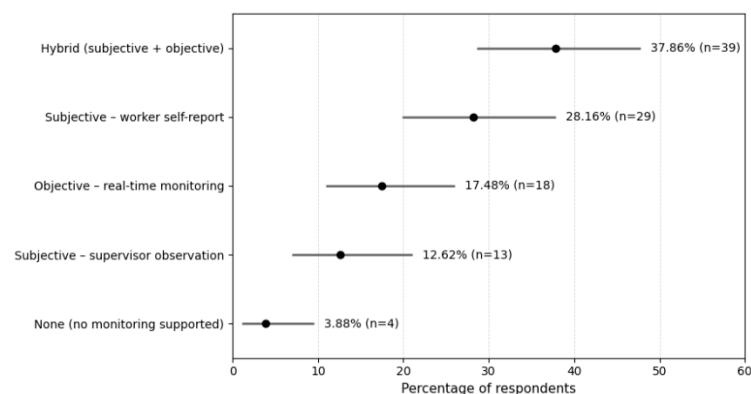


Figure 6. Preferred fatigue monitoring approach based on comfort for surveyed professionals.

The hybrid approach combining objective monitoring tools with subjective inputs was the most frequently selected option (37.86%), indicating that respondents tended to favor approaches integrating multiple sources of fatigue information rather than relying on a single method. Subjective worker self-reporting was the second-most preferred option (28.16%), suggesting relatively high comfort with worker-centered, low-burden assessment tools. Objective real-time monitoring technologies received moderate support (17.48%), reflecting comfort with technology-based methods, though to a lesser extent than approaches involving direct human input. Supervisor-based observational methods accounted for 12.62% of responses, placing them below worker- and hybrid-based approaches in terms of perceived comfort. Only a small proportion of respondents (3.88%) reported that no form of fatigue monitoring was acceptable, indicating that outright rejection of fatigue monitoring was uncommon within the sample.

In addition to comfort-based preferences, respondents were asked to indicate which fatigue monitoring approaches they considered sufficiently reliable to support job-site decision-making. Whereas comfort reflects perceived feasibility and ease of implementation, perceived reliability captures respondents' confidence in a method's ability to produce dependable information for safety-related decisions. Figure 7 summarizes these reliability-based preferences across the evaluated monitoring approaches. Dots represent observed proportions; horizontal lines indicate exact 95% binomial confidence intervals.

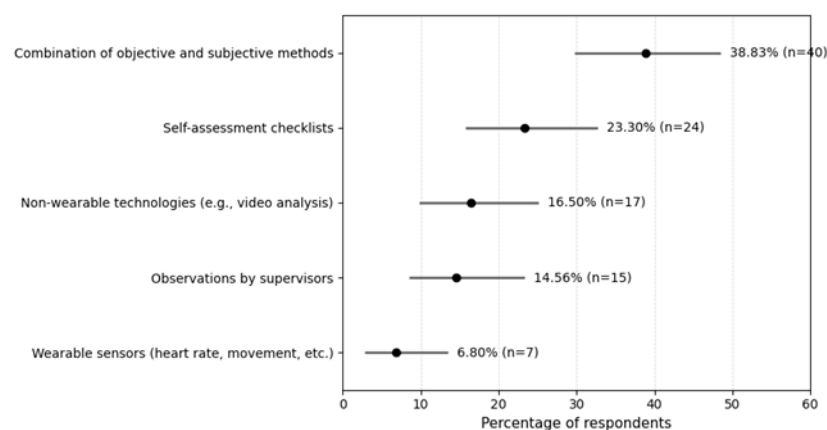


Figure 7. Preferred fatigue monitoring methods for reliable job-site decision-making ($N = 103$).

The horizontal lines in Figure 7 represent 95% confidence intervals for each reported proportion, illustrating the uncertainty associated with respondents' reliability judgments and indicating wider variability for lower-frequency responses. The combined use of objective and subjective methods was most frequently identified as the most reliable approach for job-site decision-making. Notably, wearable sensors ranked lowest despite their capacity to provide continuous physiological data. Collectively, these results indicate that while there is increasing interest in technologically advanced solutions, practical factors such as usability, training, and cultural acceptance remain decisive. The strong endorsement of combined approaches underscores the importance of hybrid systems that merge the practicality of subjective tools with the objectivity of sensor-based or observational data, thereby enhancing reliability and acceptance in safety management.

4.4. Familiarity with Subjective Fatigue Assessment Methods

By examining familiarity across roles, project contexts, and tool types, we could highlight where knowledge is concentrated, where gaps persist, and how these patterns shape the feasibility of implementing fatigue detection in real-world construction settings.

To assess industry awareness and practical knowledge of subjective fatigue assessment techniques, construction professionals rated their familiarity with ten commonly used methods on a five-point scale. A score of 1 indicated complete unfamiliarity (“Never heard of it”), while 5 represented proficiency. Results are presented in Table 3, with rows ordered in descending order of average familiarity across all professional groups.

Table 3. Subjective methods of fatigue assessment for construction workers.

Subjective Assessment Method	Project Manager	Site Supervisor	Construction Worker	Safety Officer	Other Professionals	Standard Deviation	Average for All Professionals
Daily fatigue diary/log—brief entries across a shift/day	2.86	2.35	1.10	2.35	2.28	0.41	2.19
Simple self-rating (0–10 energy/tiredness)—quick self-report	2.29	2.13	1.10	2.41	2.39	0.70	2.06
Multidimensional Fatigue Inventory (MFI)—general/physical/mental fatigue dimensions	2.00	1.04	1.00	1.94	1.89	0.42	1.57
Visual Analogue Scale (VAS) for fatigue—mark on a 0–100 line	1.86	1.04	1.00	1.88	1.83	0.41	1.52
Fatigue Severity Scale (FSS)—impact of fatigue on activities	2.00	1.13	1.00	1.71	1.71	0.41	1.59
Epworth Sleepiness Scale (ESS)—daytime dozing likelihood	1.71	1.00	1.00	1.76	1.72	0.38	1.44
Karolinska Sleepiness Scale (KSS)—momentary sleepiness rating	1.86	1.04	1.05	1.53	1.06	0.41	1.31
Subjective Workload Assessment Technique (SWAT)—perceived workload	2.00	1.17	1.00	1.06	1.06	0.32	1.26
Stanford Sleepiness Scale (SSS)—single-item current alertness	1.71	1.00	1.00	1.29	1.28	0.30	1.26
Pittsburgh Sleep Quality Index (PSQI)—sleep quality over the past month	1.00	1.09	1.00	1.23	1.22	0.24	1.11

As can be seen, the highest familiarity scores were observed for daily fatigue diaries/logs and simple self-rating scales. More structured instruments, such as MFI, FSS, and PSQI, showed lower familiarity levels. Role-based differences were also evident. Site supervisors and frontline construction workers consistently reported lower familiarity across nearly all methods compared to project managers and safety officers. This disparity indicates that knowledge of fatigue assessment remains concentrated at managerial and safety oversight levels, with limited dissemination to those most directly exposed to fatigue risks. These findings highlight the importance of targeted training and simplified implementation strategies to ensure that frontline workers can engage with fatigue monitoring tools rather than relying solely on top-down oversight.

The data also suggest that simple, self-reported, and low-barrier tools dominate familiarity in the construction sector, whereas more comprehensive or clinically validated methods remain underutilized. This presents a critical challenge: while simple tools are easy to use, they risk underreporting or bias, whereas validated tools provide more reliable insights but suffer from low awareness and adoption. Bridging this gap will require training, integration into daily workflows, and simplified adaptations of validated instruments to support broader adoption in construction safety management. These results align with prior studies showing that simple, self-administered tools are more readily adopted in workplace contexts due to ease of use and minimal training requirements [93,94].

4.5. Familiarity with Objective Fatigue Assessment Methods

Using the same 1–5 familiarity scale, respondents rated their familiarity with ten objective fatigue assessment methods. Table 4 presents mean familiarity scores by role. Across all roles and methods, familiarity with objective fatigue monitoring techniques was uniformly low. No objective method exceeded a mean familiarity score of 2.0, indicating that most respondents reported little to no prior exposure. The highest familiarity was observed for wearable multisensory devices (mean = 1.51), followed by smart PPE (1.48) and ECG/HRV-based monitoring (1.44). More specialized or research-oriented techniques—such as EEG, pupillometry, voice analysis, and actigraphy—clustered near the lower bound of the scale (means $\approx$ 1.1–1.2), reflecting minimal awareness among practitioners. These findings align with prior research showing that the limited immediate applicability of such devices reduces their prevalence in practice [8,48,95].

Table 4. Familiarity of construction professionals with objective fatigue assessment methods (mean familiarity scores on a 1–5 scale; respondent-weighted).

Objective Assessment Method	Project Manager	Site Supervisor	Construction Worker	Safety Officer	Other Professionals	Standard Deviation	Average for All Professionals
Wearable multisensory, wristbands/patches/vests (temp, accelerometer, GSR, etc.)	2.143	1.40	1.18	1.59	1.22	0.39	1.51
Smart helmets/smart PPE, embedded sensors in helmets or PPE	1.43	1.74	1.05	1.88	1.28	0.34	1.48
ECG/HRV (electrocardiography/heart rate variability), cardiac signals for fatigue load	1.71	1.35	1.05	1.82	1.28	0.32	1.44
Reaction time testing (e.g., PVT), tap/response speed to detect fatigue	1.57	1.04	1.00	1.59	1.00	0.31	1.24
Blood oxygen (SpO ₂)/pulse oximetry, oxygen saturation as a fatigue correlate	1.57	1.00	1.03	1.47	1.00	0.28	1.21
EEG (electroencephalography), brain-wave monitoring for alertness/fatigue	1.57	1.04	1.00	1.23	1.00	0.24	1.17
Eye-tracking (camera-based), saccades, blink rate, gaze behavior	1.29	1.17	1.00	1.29	1.06	0.13	1.16
Pupillometry, pupil size/blink metrics (e.g., PERCLOS) indicating drowsiness	1.29	1.13	1.00	1.23	1.00	0.13	1.13
Voice analysis, changes in pitch/tone/rhythm linked to fatigue	1.14	1.17	1.03	1.06	1.22	0.08	1.12
Actigraphy, motion/sleep patterns from wrist or body sensors	1.43	1.00	1.00	1.18	1.00	0.19	1.12

When compared with subjective methods, a clear contrast emerges. Subjective tools such as simple self-rating scales and fatigue diaries achieved higher familiarity levels (overall means > 2.0), whereas no objective method reached this threshold. This pattern indicates that familiarity is strongly associated with methods that are simple to administer, require minimal equipment, and can be implemented without specialized training. In contrast, technically advanced or sensor-based approaches appear substantially less familiar across the industry sample. This finding supports prior research showing that practical and accessible methods are more likely to be adopted in workplace settings [96,97].

It is important to note that wearable devices are generally user-friendly and highly compatible with modern health monitoring systems [98–100]. However, professionals with limited exposure may have only a vague understanding of this compatibility, leading to the

mistaken belief that such devices are complex to implement. The distribution underscores that while wearable-based monitoring is beginning to gain traction, the broader set of objective methods remains poorly understood or inaccessible. This points to a continuing knowledge gap and implementation challenges that must be addressed for more advanced fatigue detection technologies to be integrated effectively into construction practice.

Role-based differences were evident but modest in magnitude. Project managers and safety officers consistently reported higher familiarity across most objective methods, whereas frontline construction workers' ratings remained near baseline levels (typically 1.0–1.1). This distribution mirrors the pattern observed for subjective methods and suggests that awareness of fatigue monitoring technologies is concentrated at managerial or supervisory levels rather than among workers most directly exposed to fatigue risk.

The results indicate a pronounced familiarity gap between subjective and objective fatigue assessment methods in construction practice. While objective approaches are increasingly discussed in research and technology development, their limited recognition among practitioners, particularly frontline workers, suggests that adoption barriers persist at the level of awareness and exposure.

4.6. Deployment Parameters

Understanding how construction professionals prefer fatigue monitoring to be deployed is essential for identifying strategies that balance safety benefits with operational feasibility. Figure 8 summarizes the distribution of preferences across five deployment strategies.

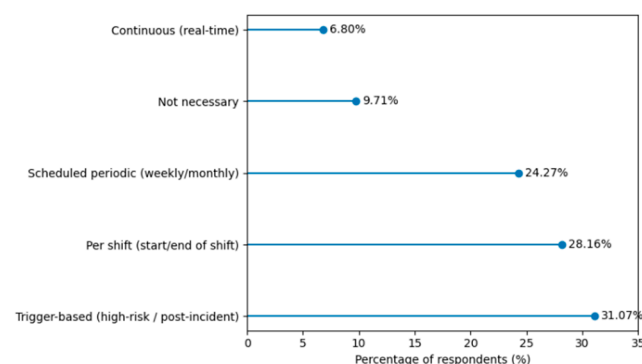


Figure 8. Preferred deployment parameters for fatigue monitoring on construction sites.

Conditional and periodic deployment models were the most frequently selected. The largest proportion of respondents (31.07%) preferred a trigger-based approach, in which fatigue monitoring is activated during higher-risk conditions or following incidents or near misses. This was followed closely by per-shift monitoring at the start and end of each shift (28.16%) and scheduled periodic monitoring conducted on a routine cadence (24.27%). Together, these responses account for more than 80% of the sample and indicate a strong preference for monitoring strategies that are event-driven or time-bounded rather than continuous.

In contrast, continuous real-time monitoring via smart PPE or wearable devices received limited support (6.80%). A small but notable share of respondents (9.71%) indicated that fatigue monitoring was not necessary, reflecting residual opposition or skepticism within the sample. Overall, the distribution shows that respondents favored deployment models that allow fatigue assessment to be targeted, intermittent, or aligned with work cycles rather than embedded as constant surveillance throughout the workday.

4.7. Operational Response When Fatigue Is Detected

Respondents were asked to indicate their preferred operational response when worker fatigue is identified. Figure 9 summarizes the distribution of responses across four action categories. Preventive and recovery-oriented responses were most strongly endorsed. The largest proportion of respondents (41.75%) favored preventive scheduling adjustments, such as modifying rosters, break timing, or shift lengths to reduce future fatigue exposure. This was followed by immediate recovery actions, including rest breaks or task rotation, selected by 33.98% of respondents. Together, these two responses account for more than three-quarters of the sample, indicating broad support for interventions that either mitigate fatigue risk prospectively or address acute fatigue in real time.

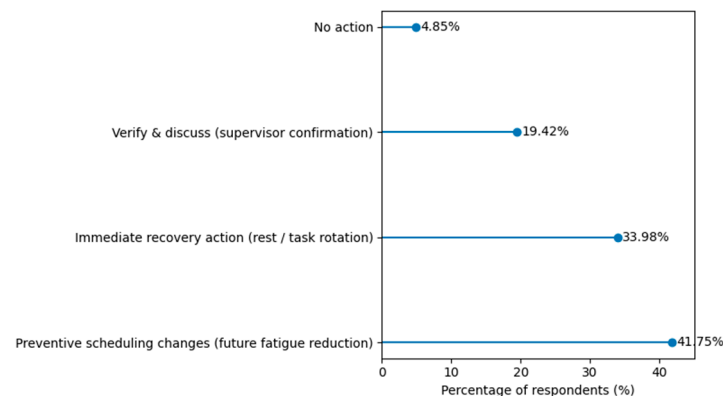


Figure 9. Preferred operational responses when worker fatigue is detected.

A smaller share of respondents (19.42%) preferred supervisor verification and discussion prior to implementing corrective actions, suggesting that managerial judgment and contextual assessment remain important components of fatigue response in some settings. Only 4.85% of participants indicated that no action was necessary, reflecting limited acceptance of fatigue as a condition that can be disregarded once detected.

The distribution indicates that respondents favored active operational responses over inaction, with preferences concentrated on strategies that either reduce the likelihood of fatigue recurrence or provide immediate safeguards when fatigue is identified.

4.8. Perceived Safety Impact

Respondents were asked to assess the expected impact of fatigue monitoring on construction site safety. Figure 10 summarizes the distribution of responses across five impact categories.

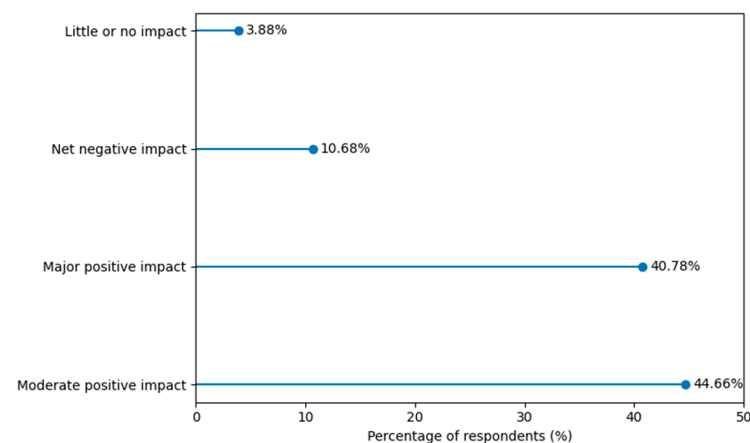


Figure 10. Perceived impact of fatigue monitoring on construction site safety.

The largest proportion of respondents (44.66%) anticipated a moderate positive impact, while a similar share (40.78%) expected a major positive impact. Together, these responses account for more than 85% of the sample, indicating broad agreement that fatigue monitoring can contribute meaningfully to safety performance when implemented in practice. In contrast, relatively few respondents anticipated neutral or adverse outcomes. A small proportion (3.88%) reported that fatigue monitoring would have little or no impact, while 10.68% indicated concern about a potential negative impact. The distribution suggests that most respondents viewed fatigue monitoring as a supportive safety intervention rather than a disruptive or ineffective measure, although a minority expressed reservations regarding its consequences.

4.9. Qualitative Insights from Open-Ended Responses

Open-ended comments provided additional context for these perceptions. Responses highlighted variation in attitudes related to experience level, role, and site culture. Several respondents, particularly those with longer industry tenure, expressed reservations regarding wearable or continuous monitoring, frequently referencing discomfort during physically demanding tasks and uncertainty about how monitoring data might be used. In contrast, comments from safety personnel and less experienced workers more often emphasized the perceived fairness and credibility of hybrid approaches that combine subjective reporting with objective indicators. Across roles, respondents noted that acceptance of fatigue monitoring was influenced by how it was framed and communicated at the site level, with greater support reported when monitoring was presented as a safety support mechanism rather than a performance surveillance tool.

4.10. Reliability and Validity Considerations (Exploratory)

Given the exploratory nature of this study, reliability and validity assessments were conducted to the extent permitted by the available data. For multi-item groupings, such as familiarity ratings across different monitoring methods, internal consistency was evaluated using Cronbach's alpha. Cronbach's alpha is calculated as:

$$\alpha = \frac{k}{k-1} \left(1 - \frac{\sum \sigma_i^2}{\sigma_{total}^2} \right)$$

K : number of items in the scale,

σ_i^2 : variance of each individual item,

σ_{total}^2 : variance of the total composite score.

The familiarity scale, comprising three items (subjective methods, objective methods, and hybrid methods), yielded a Cronbach's alpha of $\alpha = 0.72$, indicating acceptable internal consistency for exploratory research. The comfort scale, constructed using the same three method categories, produced $\alpha = 0.68$, reflecting moderate but acceptable coherence among items. The perceived reliability scale demonstrated the strongest internal consistency ($\alpha = 0.75$), suggesting that respondents evaluated the trustworthiness of different monitoring approaches in a relatively consistent manner.

5. Discussion

Fatigue monitoring has received increasing attention as a potential mechanism for improving safety outcomes in construction; however, questions remain regarding how such systems are perceived, trusted, and operationalized in real job-site environments. This study contributes to the literature by moving beyond technical feasibility and examining fatigue monitoring from the perspective of construction professionals across roles, focusing on familiarity, perceived reliability, deployment preferences, operational response, and anticipated safety impact. Across roles and experience levels, the findings reveal a consistent

pattern: subjective methods remain the most familiar and accessible, hybrid approaches are perceived as the most reliable and acceptable, and deployment preferences favor flexible, task-aligned strategies over continuous monitoring. Together, these results clarify how fatigue monitoring can transition from conceptual interest to actionable safety practice within construction environments.

5.1. Familiarity–Reliability Tradeoff in Fatigue Monitoring Approaches

The findings of this study reveal a systematic tradeoff between worker familiarity and perceived reliability across fatigue monitoring approaches, which has direct implications for implementation in construction settings. Subjective methods were consistently rated as the most familiar, reflecting their simplicity, low technological burden, and alignment with established work practices. In contrast, objective and sensor-based approaches, despite their potential to provide continuous and unbiased data, were associated with markedly lower familiarity, particularly among frontline workers. Hybrid approaches that integrate subjective inputs with objective or observational data occupied an intermediate position, achieving comparatively high perceived reliability while retaining moderate levels of familiarity.

This tradeoff suggests that adoption of fatigue monitoring in construction is governed not solely by technical capability but also by the degree to which monitoring approaches align with users' experience, trust, and operational expectations. Methods perceived as highly reliable but unfamiliar may face resistance or limited uptake, while highly familiar methods may lack the perceived rigor needed to inform critical safety decisions. Hybrid approaches appear to mitigate this tension by preserving worker involvement while enhancing informational robustness, thereby supporting both acceptance and decision credibility.

Figure 11 synthesizes this relationship into a worker familiarity–perceived reliability tradeoff framework that maps fatigue monitoring approaches into distinct implementation zones. The framework illustrates how different combinations of familiarity and reliability correspond to feasible deployment contexts, ranging from introductory exposure and low-risk applications to preferred implementation in safety-critical operations.

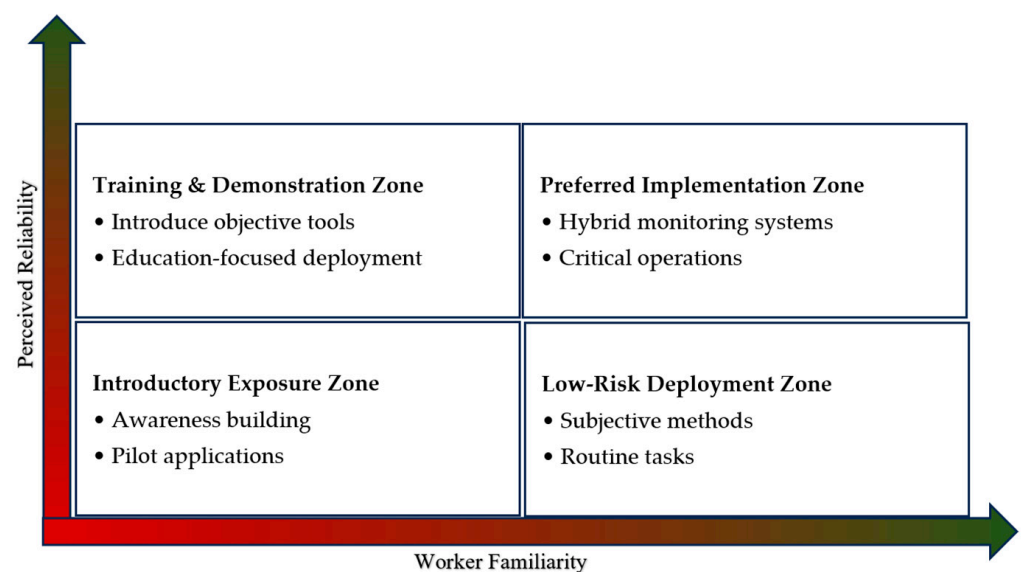


Figure 11. Worker familiarity–perceived reliability tradeoff framework for fatigue monitoring implementation in construction.

5.2. Barriers to Adoption: Human, Operational, and Organizational Constraints

Beyond stated preferences, the findings clarify why fatigue monitoring—particularly objective and continuous sensing—remains limited in construction practice. Respondents consistently identified a set of interrelated barriers that extend beyond technical feasibility and instead reflect the socio-technical conditions under which monitoring systems are introduced and used on construction sites. These barriers can be categorized in four groups as seen in Table 5. They can explain the low familiarity with objective methods, the limited support for continuous monitoring, and the preference for episodic or trigger-based deployment observed in the results.

Table 5. Key Barriers Influencing Fatigue Monitoring Adoption in Construction.

Barrier Category	Description	Implication for Implementation
Human and Cognitive Factors	Perceived intrusiveness, discomfort with sensors, trust in monitoring outputs, and self-report bias.	Favor low-burden tools and transparent data-use policies to build trust.
Operational Constraints	Interference with PPE, mobility restrictions, and sensitivity to site conditions (heat, vibration, dust).	Prioritize episodic or task-triggered deployment over continuous sensing.
Organizational and Cultural Barriers	Privacy concerns, resistance to surveillance, lack of formal policies, and crew norms.	Embed monitoring within safety culture rather than productivity enforcement.
Resource and Training Limitations	Costs of hardware, training demands, and data management or IT capacity.	Adopt phased implementation and scalable systems aligned with site resources.

Importantly, these barriers do not indicate rejection of fatigue monitoring as a safety concept. Rather, they reflect perceived misalignment between monitoring technologies and construction work practices, organizational structures, and decision-making processes. This misalignment helps explain why wearable and continuous sensing technologies, despite their demonstrated value in other occupational and health contexts, ranked low in both familiarity and perceived reliability among construction professionals in this study.

5.3. Deployment Preferences and Operational Fit

Deployment preferences underscore the importance of aligning fatigue monitoring with everyday construction operations. Respondents most strongly favored trigger-based and per-shift monitoring, indicating that fatigue is viewed as a condition that fluctuates with task demands, work schedules, and risk exposure rather than as a constant state. Monitoring linked to high-risk conditions, incidents, or shift transitions was perceived as both effective and operationally manageable. Periodic, sitewide checks were also supported as a way to establish baseline awareness without disrupting daily workflows. From an implementation perspective, these preferences support a graduated deployment approach in which monitoring intensity increases in response to elevated risk rather than being applied uniformly across all tasks and workers.

5.4. Operational Responses to Detected Fatigue

When fatigue is detected, respondents favored a combination of preventive and immediate responses. Scheduling and workload adjustments were most strongly supported, indicating that fatigue is widely viewed as a systemic issue tied to work organization rather than an individual shortcoming. Immediate recovery actions, such as rest breaks or task rotation, were also endorsed, reflecting recognition of the short-term safety risks associated with acute fatigue.

Supervisor verification was viewed as a complementary step, highlighting the continued importance of managerial judgment in interpreting monitoring information within specific work contexts. Notably, very few respondents supported taking no action, suggesting limited acceptance of fatigue as an unavoidable aspect of construction work. These preferences point to a layered response approach in which preventive planning, real-time mitigation, and supervisory discretion function together to manage fatigue-related risk.

5.5. Perceived Safety Impact and Workforce Trust

The perceived safety impact of fatigue monitoring was overwhelmingly positive. More than 85% of respondents anticipated moderate to major safety benefits, particularly when monitoring is integrated into broader safety management systems. At the same time, a small but meaningful minority expressed concern that monitoring could increase stress or undermine trust if implemented poorly.

Open-ended responses help clarify these views. More experienced workers frequently emphasized concerns related to comfort, privacy, and long-standing norms of endurance, whereas safety personnel and newer workers focused on accuracy, fairness, and the value of hybrid approaches. Together, these perspectives suggest that acceptance depends less on the monitoring technology itself than on governance and framing. Fatigue monitoring is more likely to be accepted when positioned as a supportive safety measure rather than as a tool for performance surveillance.

5.6. Technology Acceptance and the TAM Framework

The patterns observed in this study resonate strongly with the Technology Acceptance Model (TAM), which posits that technology adoption is primarily driven by two user perceptions: Perceived Ease of Use (PEOU) and Perceived Usefulness (PU). In the context of fatigue monitoring, familiarity with a method closely parallels PEOU—construction professionals who are more familiar with a tool perceive it as less burdensome and easier to integrate into their workflows. Correspondingly, perceived reliability functions analogously to PU, capturing respondents' confidence that a method will deliver actionable information for safety decision-making. The study's finding that subjective tools score highest on both familiarity and comfort, while hybrid approaches are preferred for reliability, mirrors TAM's prediction that users gravitate toward technologies that balance usability with utility. The relatively low uptake of continuous wearable sensing, despite its technical capability, aligns with TAM's emphasis on subjective perception over objective performance: if practitioners do not perceive a technology as easy to use or sufficiently useful within their specific work context, adoption will remain limited regardless of the technology's actual accuracy. These findings suggest that implementation strategies for fatigue monitoring should explicitly target both TAM constructs—improving familiarity and usability (PEOU) through training and simplified interfaces while demonstrating concrete safety benefits (PU) through pilot programs and outcome reporting.

5.7. Toward an Evidence-Informed Implementation Framework

Synthesizing these findings, this study proposes a Fatigue Monitoring Implementation Framework comprising four interconnected components:

- (1) alignment of method selection with worker familiarity and perceived reliability,
- (2) anticipation of human, operational, and organizational barriers,
- (3) deployment strategies tailored to task risk and workflow constraints, and
- (4) a staged implementation roadmap emphasizing communication, training, and trust building.

Figure 12 presents a step-by-step implementation roadmap for systematically deploying fatigue monitoring programs in construction projects. The roadmap translates the

study's empirical findings on familiarity, perceived reliability, deployment preferences, and adoption barriers into a structured decision process that aligns monitoring strategies with real-world operational constraints. Rather than treating fatigue monitoring as a purely technological solution, the framework emphasizes readiness assessment, governance, and iterative refinement to support sustainable adoption. The process begins by scoping task-specific fatigue risks and workforce characteristics, then guides decision-makers through method selection, deployment strategy, and pilot testing. A feedback loop ensures that tools and procedures are adjusted based on usability and trust before scaling across the project. By integrating monitoring into existing safety routines and organizational practices, the roadmap provides a practical pathway for moving from exploratory assessment to the routine and accepted use of fatigue monitoring on construction sites.

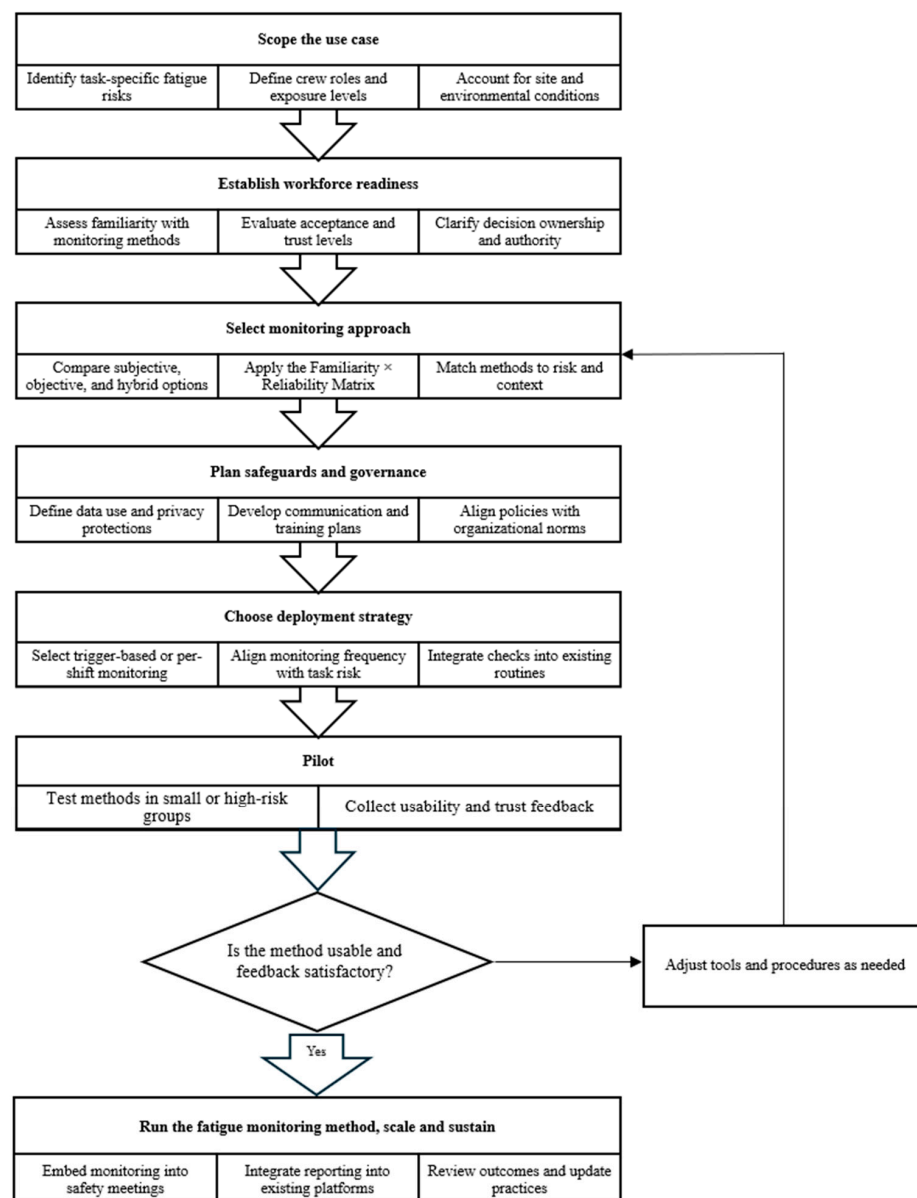


Figure 12. Implementation roadmap for systematically deploying fatigue monitoring programs.

5.8. Contributions, Statistical Depth, and Future Research

This study makes a focused contribution to construction safety research by advancing fatigue monitoring from a predominantly technical concept to an implementation-ready safety strategy. First, it provides a role-inclusive, practitioner-centered assessment of fatigue

monitoring perceptions, capturing viewpoints across the construction safety decision chain. By grounding the analysis in practitioner experience rather than laboratory performance alone, the study directly addresses the gap between fatigue monitoring research and field-level adoption.

Second, the study integrates familiarity, perceived reliability, deployment preferences, and operational responses into a coherent implementation framework. The Worker Familiarity $\times$ Perceived Reliability Matrix, implementation barriers model, and deployment roadmap collectively demonstrate that adoption is driven less by technological capability than by operational fit, organizational trust, and governance. This shifts the discourse from “which technology works best” to “which strategies can be realistically embedded into construction workflows.”

Third, the study contributes methodologically by operationalizing adoption-critical constructs—such as trust, intrusiveness, usability, and deployment context—that are often discussed qualitatively but rarely structured empirically in construction safety research. Acceptable internal consistency across exploratory scales supports their use as a foundation for future confirmatory analysis.

The statistical approach is intentionally exploratory and aligned with the study’s objectives. Descriptive statistics, dispersion measures, confidence intervals, and reliability assessments are appropriate for characterizing industry readiness and informing implementation decisions rather than testing causal mechanisms. The findings generate clear pathways for future research, including role-based hypothesis testing using ordinal or multinomial models, factor-analytic validation of latent constructs, and longitudinal or pilot-based evaluations of deployment strategies and trust dynamics.

5.9. Study Limitations

The findings should be interpreted in light of several limitations. The convenience sample limits generalizability, and the modest sample size constrained advanced psychometric validation. Self-reported familiarity and perceptions may reflect limited exposure rather than informed evaluation of technologies. Nonetheless, these limitations do not undermine the study’s value; rather, they underscore its role as an early, practitioner-grounded step toward evidence-based fatigue monitoring implementation in construction.

6. Conclusions

This study advances understanding of how construction professionals perceive and evaluate subjective and objective fatigue detection methods, offering one of the first role-inclusive perspectives on this critical safety issue. While subjective tools remain the most familiar and accessible, objective methods are increasingly recognized for their potential accuracy, and professionals see the greatest promise in hybrid approaches that combine the usability of self-reported measures with the precision of sensor-based monitoring, suggesting that integration, rather than replacement, is the most viable pathway forward. From a practical standpoint, the study underscores that successful fatigue monitoring in construction will depend not on the availability of technology alone but on its alignment with the realities of field practice. Preferences for event-triggered, per-shift, or periodic monitoring over continuous surveillance highlight the need for deployment models that balance efficiency, worker acceptance, and operational feasibility, while the emphasis on preventive scheduling adjustments and immediate recovery responses points to the importance of tiered management strategies that can address both acute risks and long-term well-being. The study also highlights persistent knowledge gaps, particularly among frontline workers, which, if unaddressed, may limit adoption and reduce effectiveness, underscoring the need for targeted training, simplified tools, and clear communication strategies to ensure

monitoring systems are understood and trusted by those most affected. By capturing the perspectives of professionals across multiple roles, the research contributes valuable insights that can guide industry stakeholders in designing fatigue management programs that are both evidence-based and practicable. Looking ahead, future research should pilot hybrid systems in real projects, evaluate cost–benefit tradeoffs, and explore long-term acceptance across different workforce segments. With thoughtful implementation, fatigue monitoring can become a cornerstone of modern construction safety management, supporting not only productivity but also the health and well-being of workers at the heart of the industry.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
BLS	Bureau of Labor Statistics
ECG	Electrocardiography
EEG	Electroencephalography
GSR	Galvanic Skin Response
HRV	Heart Rate Variability
IoT	Internet of Things
MFI	Multidimensional Fatigue Inventory
PERCLOS	Percentage of Eye Closure
PPE	Personal Protective Equipment
PVT	Psychomotor Vigilance Test
SpO ₂	Peripheral Capillary Oxygen Saturation

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