

Research Article



Assessing Fatigue in Electrical Workers Working at Height: Investigating the Potential of LF/HF Ratio and ETCO₂ as Key Physiological Indicators

Linhui Sun^{1,2}, PhD.; Yuhao An^{1,*}, MS.; Xiaofang Yuan^{1,2}, PhD.; Huiling Zhang¹, MS.; Fangming Cheng², Phd.; Zheng Li³, Phd.

¹School of Management, Xi'an University of Science and Technology, China;

²School of Safety Science and Engineering, Xian University of Science and Technology, Xi'an 710054, China

³Institute of Management Science, Ningxia University, Yin'chuan 750021, China

*Corresponding Author: Yuhao An

Abstract:

Background: Electrical workers performing tasks at height are exposed to unique physical and mental stressors that significantly increase their risk of fatigue, which can compromise safety and performance. Traditional fatigue assessments often overlook the physiological indicators that could provide a more comprehensive understanding of fatigue in such demanding environments.

Objective: To explore the sensitivity of ETCO₂ and LF/HF as potential indicators for daily work-related fatigue in electrical workers working at height, by examining their variations before and after work sessions. This research will determine their potential for integration into fatigue assessment systems.

Methods: The study involved 44 experienced male electrical workers working at height from J City Electric Power Company. Researchers measured LF/HF, ETCO₂, and FS-14 scores at four intervals: before and after morning and afternoon work sessions, aiming to capture changes in autonomic nervous system activity, respiratory efficiency, and subjective fatigue levels.

Results: After morning and afternoon sessions, FS-14 scores and physiological indicators LF/HF and ETCO₂ significantly increased, indicating induced fatigue and physiological stress in Electrical Workers Working at Height. The Wilcoxon Signed-Rank Test confirmed these changes, highlighting the sensitivity of these indicators to the work demands of these workers.

Conclusions: Findings demonstrate a correlation between LF/HF, ETCO₂, and subjective fatigue, highlighting the complex nature of fatigue in electrical work influenced by autonomic and respiratory responses. Integrating these indicators into fatigue assessment systems for electrical workers at height shows promise for future management strategies in demanding environments.

Keywords: Physiological Indicators; Preventive measures; Occupational Safety; Respiratory Markers in Fatigue; Cardiovascular Stress Indicators

Introduction

“What is fatigue?” Many scholars have provided different definitions of human fatigue, which, for a long time, has sparked considerable debate in the scientific community. However, there still needs to be a consensus on a definitive definition of fatigue in the academic community.

One perspective views it as an inability to maintain consistent activity intensity, primarily due to bodily function deterioration under specific environmental conditions, leading to alterations in physiological and psychological states and subsequent discomfort, which can further result in feelings of fatigue, weakness, lack of energy, and difficulty concentrating (Yoon et al., 2023).

Fatigue critically influences worker performance, serving as a substantial causative factor in accidents (Parenteau et al., 2023). Thus, actively monitoring fatigue in workers is essential to mitigate cognitive impairments and physical decline caused by it, thereby eliminating potential safety hazards associated with fatigue.

In this context, the challenge becomes understanding fatigue and developing reliable methods to assess it across various industries, each with unique environmental and operational demands. The direct impact of industry-specific fatigue assessment on worker safety and overall productivity underscores the need for such evaluations. As sectors ranging from construction to aviation have begun to realize, an accurate fatigue assessment can prevent accidents and enhance operational efficiency. This necessity raises the question of how different work environments assess fatigue and the effectiveness of these methods in capturing the multifaceted nature of fatigue.

Numerous industries currently explore fatigue characteristics among their workers, aligning with the unique demands of their operational environments and formulating respective fatigue assessment systems. These sectors include construction (Zhang et al., 2023), assembly line (Abdous et al., 2023), aviation crew (Wen et al., 2023), maritime (Fan & Yang, 2024), logistics and supply chain (Winkelhaus et al., 2018), railway passenger services (Phillips, 2023), firefighters (Paulo et al., 2023), and the military (Heilbronn et al., 2023). However, the plight of workers in high-voltage electrical tasks at elevated heights receives limited scholarly attention. These workers, equipped with sophisticated safety gear, climb poles approximately 15 meters tall, performing intricate high-voltage electrical operations. Their work requires considerable physical effort, intense focus, and adaptability to the varying and demanding high-altitude conditions.

Consequently, integrating an array of rigorous and scientific physiological indicators into the fatigue assessment framework for these electrical workers working at height is paramount for thoroughly elucidating the complex interplay between fatigue and physiological responses in challenging work environments. The significant physiological stress, particularly on the cardiovascular and

respiratory systems in such settings, is noteworthy. To assess fatigue in this group, we focus on two key indicators: the Low Frequency/High-Frequency ratio (LF/HF) and End-Tidal Carbon Dioxide (ETCO₂).

The LF/HF ratio, a pivotal metric in Heart Rate Variability (HRV) analysis, is extensively utilized to reflect the autonomic nervous system's activity. The Low Frequency (LF) component generally aligns with sympathetic nervous system activity, while the High Frequency (HF) component correlates with parasympathetic nervous system activity. This ratio, indicative of the dynamic balance between sympathetic and parasympathetic controls, provides insights into the body's physiological adjustments to stress and fatigue (Anwer et al., 2023; Catai et al., 2020). Previous research established the LF/HF ratio in heart rate variability (HRV) analysis to assess physiological stress responses in various contexts. Burlacu et al. (2021) highlighted in their systematic review that HRV could serve as a valuable biomarker for monitoring drivers' sleepiness, fatigue, and stress levels. However, they also pointed out the need for extensive empirical research to validate these findings further. Building on this, Srinivasan et al. (2024) demonstrated through a placebo-controlled randomized trial that the LF/HF ratio was positively correlated with the degree of fatigue in drivers, underscoring its potential as a reliable measure in fatigue assessment. Additionally, Boffet et al. (2024) used the LF/HF ratio to evaluate physiological responses during cognitive tasks in healthy individuals, showcasing its utility in monitoring mental fatigue. Chen et al. (2020) extended the application of HRV analysis, particularly the LF/HF ratio, to miners working in high-altitude and cold environments, demonstrating its reliability in detecting fatigue under harsh working conditions.

While these studies highlight the significant value of the LF/HF ratio across various fields, its application to Electrical Workers Working at Height still needs to be explored. These workers encounter unique physical and mental challenges as they perform complex and demanding tasks in harsh environments characterized by risks such as falls, electrocution, and rapidly changing conditions (wind speed, temperature, humidity), along with the difficulties associated with emergency response (rescue or equipment

support). The low level of automation in their tasks, which rely heavily on precise manual operations, substantially increases their risk of experiencing fatigue and the potential dangers associated with fatigue-induced errors.

If the effectiveness of the LF/HF ratio is validated in this context, it could pave the way for developing wearable monitoring devices that continuously assess workers' fatigue levels, thereby enhancing both safety and productivity. ETCO₂ is another important indicator for measuring respiratory efficiency and metabolic status. ETCO₂ represents the highest concentration of carbon dioxide in exhaled air and is commonly used to monitor patients' respiratory status and blood carbon dioxide levels. Clinicians in clinical settings employ ETCO₂ to evaluate respiratory and circulatory conditions in patients with critical illnesses. Research by Thacker et al. (2023) underscored the importance of ETCO₂ in monitoring critically ill patients, indicating its pivotal role in assessing respiratory and metabolic status. ETCO₂ measurement, commonly employed in clinical settings as a prognostic indicator during patient resuscitation, has yet to be explored beyond its traditional medical applications. Recently, a few scholars have begun to extend the use of ETCO₂ into non-clinical settings, particularly in studies related to respiratory function in high-altitude or low-oxygen environments. For instance, research by Venkat et al. (2021) has demonstrated significant findings regarding the effects of high altitude on sleep and the respiratory system, highlighting the versatility of ETCO₂ as a tool for assessing respiratory changes in challenging environments. Furthermore, there has been an emerging trend among researchers to utilize ETCO₂ as a marker for fatigue. Studies by van Campen et al. (2023) and Ramakers et al. (2023) explored the role of ETCO₂ in monitoring fatigue levels in various conditions, such as chronic fatigue syndrome and stress-related disorders, illustrating its relevance beyond traditional respiratory assessments.

Given these insights and considering the unique working conditions of Electrical Workers Working at Height, we aim to investigate whether ETCO₂ levels exhibit significant changes before and after their tasks, correlating with their fatigue levels. The high physical and mental demands

placed on these workers and the environmental challenges they face make it essential to explore innovative methods for fatigue detection. ETCO₂, with its proven utility in both clinical and non-clinical settings, presents a promising avenue for assessing the physiological impact of such strenuous work. Therefore, this study aims to investigate the changes in LF/HF and ETCO₂ concentrations before and after electrical work at height. The results will determine whether these indicators can be integrated into the fatigue assessment system for electrical workers working at height and provide insights for fatigue research in similar work environments.

Additionally, to ensure the changes in LF/HF and ETCO₂ primarily result from fatigue states emerging post-high-altitude electrical work, this study incorporates the FS-14 scale to assess the fatigue levels of electrical workers working at height. The FS-14 scale, developed by Chalder et al. (1993), is a questionnaire designed to determine subjective levels of human fatigue. It includes 14 items covering multiple dimensions of fatigue, such as physical and mental fatigue and fatigue perceptions related to daily activities. The results of this study will determine the feasibility of integrating LF/HF and ETCO₂ into the fatigue assessment system for electrical workers working at height. Additionally, it will provide insights for assessing fatigue states in workers operating in similar work environments.

2. Method

Considering that electrical workers working at height belong to a unique professional category, this study meticulously accounts for the characteristics and environment of their practical work, resulting in the design of a targeted experiment.

2.1 Experimental Design

We conducted this experiment at the J City Electric Power Company, randomly selecting 44 frontline electrical workers with over five years of experience as participants. The average age of the participants was 29±7 years, all male. None had a history of heart disease or pulmonary dysfunction. The experimental period was in July, during which J City experienced high temperatures and frequent rainfall. The participants were required to complete flood season electric power system maintenance work and routine training, entailing

high work intensity, making this period more representative and practically significant.

By studying the work tasks and daily training plans of electrical workers working at height and

collaborating with company supervisors and instructors, we established the experiment and measurement tasks as detailed in the following Table 1:

Table 1 Schedule of Experimental Activities and Safety Measures for Electrical Workers Working at Height

Time	Activity	Safety Considerations
8a.m.-8.30a.m.	Measure FS-14,LF/HF, ETCO ₂	Stop the measurement if discomfort arises during monitoring
8.30a.m.-12p.m.	Construction Equipment Maintenance and Power Operations	Personnel Protection, Tool Injuries, Object Strikes, Gas Poisoning, Operational Injuries, Electrical Risks
12p.m.-12.30p.m.	Measure FS-14,LF/HF, ETCO ₂	Stop the measurement if discomfort arises during monitoring
12.30p.m.-2p.m.	Eating Lunch and Lunch Break	Urge subjects to dine and rest promptly, avoiding unrelated activities
2p.m.-2.30p.m.	Measure FS-14,LF/HF, ETCO ₂	Stop the measurement if discomfort arises during monitoring
2p.m.-6p.m.	Pole Climbing Training	Risk of Being Trapped at Heights, Falling Objects from Heights, Risk of Falling from Heights
6p.m.-6.30p.m.	Measure FS-14,LF/HF, ETCO ₂	Stop the measurement if discomfort arises during monitoring

We implemented the following plan to collect experimental data: measuring LF/HF, ETCO₂, and the FS-14 scale at 8 a.m., 12 p.m., 2 p.m., and 6 p.m. These times corresponded to before and after the participants' morning and afternoon work sessions. This measurement schedule effectively addressed challenges related to participant absence due to shift changes and emergencies. Additionally, during the experiment, the company uniformly managed the participants' daily routines, enhancing the persuasiveness of the experimental data.

We set up the experimental site in the participants' work rest area, with strict control over noise and light intensity to minimize the influence of extraneous variables on the participants. Researchers instructed and demonstrated the operation of measurement instruments to the participants in advance. Before starting the measurements, researchers assured the participants of the safety and reliability of the process, reducing their concerns, and guided them in independently donning and using the measuring instruments.

All procedures received approval from the Ethics Committee of the School of Management, Xi'an University of Science and Technology. We conducted all indicator measurements and participant experimental tasks as described in this study and relevant guidelines. All participants provided written informed consent and received a compensation of 200 RMB each.

2.2 LF/HF Measurement Process

2.2.1 Electrode Setup and Participant Positioning:

Attach silver ion electrodes to the participant's inner sides of both wrists and 2 centimeters above the left ankle. Apply gentle, consistent pressure to each electrode for optimal skin contact.

Connect the electrodes to the LF/HF measuring device using lead wires, ensuring secure and stable connections. Instruct participants to lie prone, emphasizing the importance of remaining motionless and silent during the measurement.

2.2.2 Measurement Execution and Data Recording:

Conduct the measurement for 8 minutes, maintaining close supervision to adhere to the

protocol. After the measurement, meticulously record the LF/HF ratio from the device for analysis.

2.3 ETCO₂ Measurement Process

2.3.1 Device Setup and Initial Preparation:

Have participants attach the breathing interface to the ETCO₂ module and hold it firmly with their right hand, ensuring a tight seal between the interface and mouth. This step includes checking for air tightness to prevent any potential leakage.

2.3.2 Measurement Execution and Observation:

Position participants comfortably in front of the device in a relaxed stance. Instruct them to breathe naturally and smoothly for 5 minutes, maintaining a consistent breathing pattern. Researchers should meticulously observe the device readings during this period to ensure accuracy and consistency.

2.3.3 Conclusion and Data Recording:

At the end of the measurement, record the highest ETCO₂ concentration value noted within the 5-minute window for analysis.

2.4 FS-14 Measurement Process

2.4.1 Translation and Adaptation of the FS-14 Scale for Chinese Speakers

Our participant group consisted primarily of native Chinese speakers who found it challenging to understand the English version of the scale. To ensure the scale's accuracy and suitability, we translated the original English FS-14 scale into Chinese. In this translation process, we carefully maintained the precision and contextual consistency of the original text. This approach ensured accurate communication of each item's meaning in Chinese. We have included the original English version and the Chinese translation in the appendix.

2.4.2 Questionnaire Administration

Provided participants with detailed instructions on accurately completing the FS-14 questionnaire, ensuring clarity on the significance and meaning of each item. Encouraged participants to

independently and thoughtfully complete the questionnaire, accurately reflecting their fatigue levels.

In the forthcoming results section, we will present the data collected from our study, focusing specifically on the variations observed in LF/HF ratios, ETCO₂ levels, and FS-14 scores. This presentation will briefly showcase the direct outcomes of the experimental measures implemented, providing a factual basis for further in-depth discussion in subsequent sections. By delineating these empirical findings, we aim to establish a foundational understanding of the physiological and psychological impacts experienced by Electrical Workers Working at Height under the strenuous conditions of high-altitude tasks.

3. Results

3.1 Data Preprocessing

In this experiment, we collected 472 sample sets and implemented the following methods for sample processing: 1. We eliminated samples with missing data; 2. We employed box plots to identify extreme values within the samples (data points located beyond $3 * IQR$). These values noticeably exceeded the reasonable range for human objective physiological indicators, likely due to errors in data transcription or reading deviations. We chose not to replace extreme values with means or medians because we concluded that the sample size remaining after removing samples with extreme values was still ample to support the research and ensure the conclusions' scientific validity. Eventually, we secured 435 valid sample sets, distributed across four time points as follows: 109 (8 a.m.), 109 (12 p.m.), 108 (2 p.m.), and 108 (6 p.m.).

3.2 Descriptive Statistics and Results of Normality Test

The following section presents the descriptive statistical analysis, normality test indicators, and their results for LF/HF (Table 2), ETCO₂ (Table 3), and FS-14 (Table 4):

Table 2 Descriptive Statistics and Normality Test Results for LF/HF Ratios at Different Times of the Day

Time	LF/HF					
	M	Confidence Interval		SD	D	P
		LL	UL			
8a.m.	1.31	1.18	1.45	.71	.117	.000
12p.m.	1.62	1.43	1.80	.95	.137	.000
2p.m.	1.33	1.18	1.48	.80	.137	.000
6p.m.	1.42	1.28	1.56	.74	.112	.002

Table 3 Descriptive Statistics and Normality Test Results for ETCO₂ Levels Across Various Time Intervals

Time	ETCO ₂					
	M	Confidence Interval		SD	D	P
		LL	UL			
8a.m.	36.10	35.11	37.09	5.21	.064	.200
12p.m.	36.24	35.23	37.25	5.33	.094	.020
2p.m.	34.84	34.19	35.49	3.38	.060	.200
6p.m.	36.51	35.70	37.31	4.20	.084	.058

Table 4 Descriptive Statistics and Normality Analysis of FS-14 Scores Before and After Work Sessions

Time	FS-14					
	M	Confidence Interval		SD	D	P
		LL	UL			
8a.m.	4.45	4.23	4.67	1.151	.216	.000
12p.m.	6.85	6.66	7.05	1.035	.196	.000
2p.m.	5.99	5.97	6.01	.096	.529	.000
6p.m.	9.76	9.56	9.97	1.079	.202	.000

In this study, if the p-value from the normality test surpasses 0.05, it implies insufficient grounds to refute the supposition that the sample distribution aligns with normality. The sample is roughly conforming to a normal distribution. Conversely, should the normality test produce a p-value of 0.05 or lower, this furnishes ample substantiation to dismiss the postulate that the data adhere to a normal distribution, leading to the conclusion that the sample does not follow a normal distribution.

3.3 Results of the Wilcoxon Signed-Rank test

Each participant underwent multiple physiological measurements on different dates and times, enabling us to track individual physiological

changes over a specific period. This facility eased the in-depth analysis of dynamic changes in individual physiological indicators, hence categorizing the sample as non-independent.

Considering the non-normal distribution of some samples and their non-independent nature, this study employed the Wilcoxon Signed-Rank Test to evaluate the significance of differences in indicators before and after the subjects' work tasks. Excelling in analyzing non-normally distributed and non-independent samples, the Wilcoxon Signed-Rank Test (Table 5) stood as an optimal method for assessing significant variations in physiological indicators related to experimental tasks.

Table 5 Wilcoxon Signed-Rank Test Results for LF/HF, ETCO₂, and FS-14 Scores

Time	LF/HF				ETCO ₂				FS-14			
	T	SD	Z	P	T	SD	Z	P	T	SD	Z	P
8a.m.&12p.m.	3523	317.	2.16	.03	3030.	330.77	.10	.92	5995	295.	10.1	.00**
m.	.5	27	9	*	5				47	5		

2p.m.&6p. m.	3204	321. 75	.979	.32 8	3956	326.25	3.1 1	.00 **	5778	317. 66	9.09 5	.00**
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*indicates a p-value less than or equal to 0.05

** indicates a p-value less than or equal to 0.01

The elevations in LF/HF ratios, ETCO₂ levels, and FS-14 scores post high-altitude work sessions for Electrical Workers Working at Height markedly underscore the significant effects of such tasks on both physiological and psychological aspects of worker health. These outcomes not only signify acute reactions to occupational stressors but also delineate broader consequences for worker health and safety. As we engage in the subsequent discussion of these results, it is crucial to elucidate the association between these physiological changes and the real-world challenges Electrical Workers Working at Height encounter in elevated environments.

4. Discussion

4.1 FS-14

Our study found that the FS-14 scores significantly increased after participants performed high-altitude electrical work, indicating increased subjective fatigue. Specifically, the FS-14 scores rose from 4.45 to 6.85 after the morning work session and from 5.99 to 9.76 after the afternoon session. These substantial increases, validated by P-values ≤ 0.05 , show that electrical workers working at height felt notably fatigued after completing their tasks. The average FS-14 score before afternoon work (mean = 5.99) was higher than before morning work (mean = 4.45) but lower than after morning work. This suggests that lunch breaks and rest periods can reduce subjective fatigue, though not back to morning pre-work levels. The highest FS-14 score was observed after the afternoon session (mean = 9.76), highlighting a progressive accumulation of fatigue throughout the day. This accumulation is likely due to ongoing high-altitude tasks and continuous physical and mental strain, potentially affecting workers' health and efficiency.

In summary, electrical workers working at height experienced a noticeable increase in subjective fatigue after work and an accumulative effect of fatigue throughout the day. Breaks and lunchtime rest provided some relief but did not completely counteract work-related fatigue (Albulescu *et al.*,

2022; O'Neill *et al.*, 2022). These insights were vital for creating better work schedules and fatigue management strategies to maintain employee health and efficiency (Thompson, 2019).

4.2 LF/HF

The research findings indicated that LF/HF exhibited varying increases after participants completed their work tasks. Specifically, LF/HF rose from 1.31 to 1.62 after the morning work session and from 1.33 to 1.42 after the afternoon session. These observations suggested a positive correlation between the LF/HF indicator and the participants' sense of fatigue. Since fluctuations in LF/HF could reflect changes in the participants' autonomic nervous system regulation during work, the increase in LF/HF average values was likely associated with heightened psychological stress and mental fatigue levels (Ahmed *et al.*, 2022; Burlacu *et al.*, 2021). LF/HF values showed a decreasing trend after participants' lunch breaks, dropping from 1.62 post-morning work to 1.33. This change indicated that taking breaks and resting at midday could effectively reduce LF/HF. However, the specific extent and mechanisms of rest and sleep on LF/HF required more detailed and profound research.

Further statistical analysis revealed that only the median values of the morning pre- and post-work samples differed significantly (morning P-value = 0.03, ≤ 0.05). This suggested that participants had experienced increased cognitive load after prolonged skill-based tasks in the morning, leading to mental fatigue and enhanced sympathetic and reduced parasympathetic nervous activities. This result aligned with observations by Mizuno *et al.* (2011) further supporting the association between LF/HF and work-related fatigue.

However, the median values of LF/HF samples before and after afternoon work did not show significant differences (afternoon P-value = 0.328, ≥ 0.05). This may be due to the afternoon tasks involving high-intensity physical labor, with physiological declines possibly being insufficient

to cause significant changes in LF/HF. This implied that the response of the LF/HF indicator to different types of work and intensities requires further investigation.

In summary, changes in LF/HF are related to participants' fatigue perception, reflecting the workers' ability to regulate their autonomic nervous system during work, especially under continuous physical and psychological load (Boffet *et al.*, 2024). This provides crucial insights for improving work environments and employee health. Additionally, further research is needed to explore the mechanisms linking LF/HF with work-related fatigue and to develop effective interventions to alleviate work fatigue and enhance work efficiency.

4.3 ETCO₂

The research results show that the ETCO₂ levels of the participants increased to varying degrees after their work. Specifically, at the end of the morning work session, ETCO₂ rose from 36.10mmHg to 36.24mmHg, and at the end of the afternoon session, it increased from 34.84mmHg to 36.51mmHg. These findings indicate a positive correlation between ETCO₂ levels and participants' fatigue: as work duration extended, ETCO₂ levels gradually rose, showing a clear association with participants' fatigue. ETCO₂ measurements decreased after the lunch break compared to the end of the morning work, from 36.24mmHg to 34.84mmHg. This suggests that taking breaks and resting at midday can partly restore the regulatory capacity of the respiratory system. This finding emphasizes the importance of rest and lunch breaks in alleviating work fatigue and restoring physiological balance (Goffeng, 2020).

Simultaneously, the rise in ETCO₂ levels following work tasks indicates increased metabolic demands during physical exertion. Higher ETCO₂ levels suggest that the workers' bodies are experiencing heightened metabolic activity and respiratory changes, likely due to the need to meet the energy demands of strenuous physical tasks (Pleil *et al.*, 2021). While this metabolic response is essential for sustaining high levels of physical activity, it also leads to quicker depletion of energy reserves, contributing to the overall sense of fatigue.

Additionally, statistical analysis found significant differences only in the median values of ETCO₂ before and after the afternoon work, with a P-value of 0.03, indicating significance at or below the 0.05 level. This suggests that ETCO₂ level changes are more pronounced during the afternoon work period. Compared to the morning, the high workload and challenging outdoor working conditions in the afternoon might have a greater impact on the respiratory system, indicating the need for increased rest periods for the participants during afternoon work (Ioannou *et al.*, 2022). The results demonstrate a positive correlation between the ETCO₂ levels of electrical workers working at height and work-related fatigue, also highlighting the critical role of stopping work and taking lunch breaks in maintaining respiratory system stability. These findings contribute to a deeper understanding of the physiological regulation mechanisms in electrical workers working at height, providing important references for reducing work intensity and maintaining employee health.

4.4 Comprehensive Analysis

Building on the independent analyses of the FS-14, LF/HF ratios, and ETCO₂ levels, it becomes essential to integrate these measures to offer a holistic view of fatigue in electrical workers working at height. The significant post-work increase in FS-14 scores signals that workers perceive a heightened state of fatigue following their tasks. This subjective marker of fatigue, when analyzed alongside objective physiological indicators (LF/HF, ETCO₂), provides a comprehensive fatigue assessment.

The simultaneous elevation in subjective fatigue levels, as measured by the FS-14 scale (Guo *et al.*, 2020), along with objective physiological markers—specifically LF/HF (Srinivasan *et al.*, 2024) ratios and ETCO₂ (van Campen *et al.*, 2023) levels—among electrical workers working at height, underscores a complex interplay between perceived fatigue and underlying physiological mechanisms. This correlation between subjective and objective indicators provides valuable insights into the fatigue experienced by these workers in demanding environments. Specifically, the FS-14 scale, which captures subjective feelings of fatigue, including exhaustion, reduced energy, and difficulty concentrating, is instrumental in assessing the

internal states of workers (Krupp, 2004). The post-task increase in FS-14 scores indicates that workers perceive a heightened state of fatigue after their tasks. This subjective perception aligns with the physiological data, where both the LF/HF ratio and ETCO₂ levels also rise.

The concurrent increase in FS-14 scores, LF/HF ratios, and ETCO₂ levels illustrates that as workers engage in complex tasks that require significant physical and mental effort, their bodies respond by increasing energy production and consumption (as reflected by ETCO₂ (van Campen et al., 2023) and activating the stress response (as indicated by LF/HF (Burlacu et al., 2021)). This integrated response, while necessary for task performance, may exacerbate fatigue, mainly if adequate recovery time is not provided. The data also reveal that while rest periods, particularly lunch breaks, can effectively reduce fatigue, they may not fully alleviate it. This finding suggests that additional rest periods may be necessary to prevent the cumulative effects of fatigue throughout the workday. Research has shown that accidents are more likely to occur between 9:00-11:00 AM and 3:00-4:00 PM (Xiang et al., 2022), which coincide with the busiest production periods. These times represent critical points during the workday when workers are more prone to fatigue, and their physical and mental capacities are in a transient recovery phase. To mitigate fatigue-related risks, we should schedule additional short breaks around 10:00 AM and 4:00 PM. These strategically timed breaks could help maintain worker alertness and reduce the likelihood of errors, thereby enhancing overall safety and productivity.

In summary, our study provides comprehensive insights into the multifaceted nature of fatigue experienced by electrical workers working at height. By analyzing subjective fatigue levels through the FS-14 scale alongside objective physiological measures—LF/HF ratios and ETCO₂ levels—our findings underscore a complex interplay between perceived fatigue and physiological responses to demanding work conditions.

This comprehensive assessment highlights the need for better fatigue management strategies that consider both the subjective perception of fatigue and its physiological markers. While rest periods like lunch breaks offer some relief, our findings

suggest they are insufficient to alleviate fatigue fully, necessitating additional scheduled breaks to combat the accumulative effect of fatigue throughout the day. Indeed, strategically timed rest periods could significantly enhance worker safety and productivity by reducing the likelihood of fatigue-induced errors.

Further research should continue to explore the underlying mechanisms linking subjective and objective fatigue measures and develop interventions to mitigate work-related fatigue effectively. By integrating these findings into practical applications, we can better safeguard the health and efficiency of workers in high-risk environments, ensuring their well-being and operational safety.

5. Conclusions

The study has rigorously examined the fatigue experiences of electrical workers working at heights through a comprehensive review of related literature, meticulously designed experiments, and systematic data collection. We analyzed subjective perceptions of fatigue, as measured by the FS-14 scale, and objective physiological responses, including the LF/HF ratio and ETCO₂ levels, which increased significantly following work tasks. These results indicate a strong correlation between the workers' perceived exhaustion and measurable physiological changes, illustrating the physical and psychological demands placed on them.

Our findings confirm that LF/HF and ETCO₂ respond to intense job demands and reflect significant stress impacts on autonomic and respiratory systems. Notably, we observed a pattern of fatigue accumulation throughout the day that was influenced by the specific timing and nature of tasks. This underscores the need for fatigue management strategies sensitive to the differing morning and afternoon work session requirements. Additionally, our results demonstrate that while standard rest periods like lunch breaks provide some relief from fatigue, they are insufficient to reverse the effects of fatigue accumulated throughout the workday fully. This insight is crucial for developing more effective rest protocols that prevent potential safety risks and enhance overall productivity and health. Further refinement of these fatigue indicators is recommended for future studies to

explore their applicability across different high-intensity work scenarios. Investigating the long-term effects of cumulative fatigue and the effectiveness of various fatigue management strategies will provide deeper insights into the health impacts and optimal interventions necessary for these work environments. Moreover, integrating real-time fatigue monitoring in safety protocols could transform health management practices in physically demanding occupations.

In summarizing these empirical findings, our study contributes significant insights to the occupational health literature. It provides a robust basis for future research and practical applications to improve workers' safety and well-being in high-risk settings.

The study's generalizability is limited due to a relatively small and homogeneous sample size of 44 male electrical workers from a single power company, suggesting a need for a larger, more diverse cohort. Additionally, the absence of a control group poses a significant limitation. This was primarily due to the operational demands of the workers, as they could not be scheduled for a full day of rest to serve as a control. However, the physiological measurements (LF/HF and ETCO₂) captured at 8 AM before work sessions were used as baseline data, providing a reference point for comparison. Despite this, a formal control group is needed to reduce the robustness of causal inferences, as it limits the ability to attribute the observed fatigue solely to work-related tasks conclusively. Furthermore, the physiological measurements only captured specific snapshots before and after work sessions, potentially missing intra-session fluctuations. The reliance on subjective measures of fatigue, like the FS-14 scale, could also be complemented by objective performance assessments to mitigate individual bias in self-reporting. Environmental variables such as noise and weather conditions were not accounted for, which could significantly affect fatigue levels.

In future studies, efforts should be made to address these limitations. For example, researchers could consider applying for permissions that allow workers to be scheduled in shifts that include full rest days, thereby creating the opportunity to establish a control group. Additionally, expanding the study to include a larger, more diverse sample and incorporating

continuous physiological monitoring throughout the workday would provide a more comprehensive understanding of fatigue dynamics. Combining subjective assessments with objective performance measures and controlling for environmental factors would further enhance the validity and reliability of the findings.

Statements & Declarations

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Author Contributions: H.L., and Y.A. were responsible for manuscript writing, and revision Y.A., H.Z, X.Y. and were involved in designing the experiments and data collection. H.L., F.C. was responsible for data analysis. H.L., Z.L. and X.Y. provided funding support. All authors have read and agreed to the published version of the manuscript.

Ethics approval: The study was conducted according to the guidelines of the Declaration of Helsinki, and all experimental operations were carried out under professional supervision to ensure the scientific integrity and rigor of the study. The experimental procedures were approved by the Ethics Committee for college of management in Xi'an University of Science and Technology (Date:08/11/2022;No.20220079).

Consent to participate: Informed consent was obtained from all individual participants included in the study.

Consent to publish: Consent to publish was obtained from all individuals who participated in the study

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Appendix

14-Item fatigue scale

Physical Symptoms

1. Do you have problems with tiredness?
2. Do you need to rest more?
3. Do you feel sleepy or drowsy?
4. Do you have problems starting things?
5. Do you start things without difficulty but get weak as you go on?
6. Are you lacking in energy?
7. Do you have less strength in your muscles?

8. Do you feel weak?

Mental Symptoms

9. Do you have difficulty concentrating?

10. Do you have problems thinking clearly?

11. Do you make slips of the tongue when speaking?

12. Do you find it more difficult to find the correct word?

13. How is your memory?

14. Have you lost interest in the things you used to do?