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PHYSIOLOGICAL AND PERCEPTUAL EVALUATION OF RIDING COMFORT IN MOUNTAINOUS RAILWAYS

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Abstract

This study investigates riding comfort in mountainous tourism rail transit by integrating subjective passenger feedback with objective physiological and environmental data. Using the Lijiang Yulong Snow Mountain line as a case study, the research identifies key factors influencing passenger comfort and proposes strategies for improvement. Physiological signals, including electrocardiography (ECG), electromyography (EMG), and skin conductance, were recorded alongside environmental parameters such as vibration, noise, and altitude. Factor analysis revealed three significant components: physical comfort, environmental adaptability, and service experience. High-altitude sections above 3000 m led to an 18% reduction in heart rate variability (HRV) ($p < 0.01$) and were strongly associated with passenger fatigue. Sharp curves with a radius below 150 m increased muscle activity by 22% ($p < 0.001$). The results suggest that multi-faceted evaluation of ride comfort in mountainous rail should combine passenger perception with environmental and physiological data like HRV, EMG, and skin conductance. Targeted strategies, including adaptive suspension systems and altitude-adjustive seating, are proposed to improve comfort in complex terrains. Beyond the case of Lijiang, the results provide practical insights for the design, operation, and management of tourism rail systems in other Asian mountainous regions, thereby supporting sustainable tourism development and enhancing passenger-centered travel experiences.

Keywords: Mountain Railways, Riding Comfort, Physiological Assessment, Subjective Evaluation, Tourism Transportation

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Introduction

Tourism rail transit in mountainous regions presents unique challenges and opportunities in promoting sustainable tourism while ensuring passenger comfort. Unlike conventional urban rail systems, mountainous lines often traverse steep gradients, sharp curves, and high-altitude environments, where variations in terrain, climate, and operational dynamics can significantly influence the travel experience. As tourism increasingly shifts toward immersive experiences in natural landscapes, passenger comfort has emerged as a critical factor affecting satisfaction, safety perception, and willingness to travel (Lieophairot & Rojniruttikul, 2024). Comfort in rail transit is not solely a function of mechanical performance but encompasses physiological, psychological, and environmental dimensions, requiring a multifaceted evaluation approach. Traditional assessments of rail passenger comfort have relied heavily on subjective surveys and questionnaires to gauge perceptions of ride quality, vibration, noise, and service experience. While valuable, subjective data are inherently influenced by individual variability, cultural expectations, and situational factors, potentially limiting their accuracy and comparability. To complement subjective evaluations, objective measurements such as vibration analysis, noise monitoring, and physiological signal recording have gained attention as reliable indicators of passenger responses to rail dynamics. Metrics such as heart rate variability (HRV), electromyography (EMG), and skin conductance provide quantifiable evidence of stress, fatigue, and discomfort, allowing researchers and engineers to identify critical factors that may not be apparent through self-reported feedback alone.

Tourism-oriented railways in mountainous regions are experiencing rapid growth, driven by increasing demand for sustainable and immersive travel experiences. In China alone, passenger volume on tourist rail lines has grown by over 25% in the past decade, with similar expansions observed in Southeast Asia, where rail systems are being promoted as eco-friendly alternatives to road transport (Tolkach et al., 2016). Mountain railways, such as the Qinghai–Tibet Railway in China and the Darjeeling Himalayan Railway in India, have become not only critical transport links but also iconic cultural assets, demonstrating the rising significance of rail in tourism development across Asia. Despite this growth, existing research on riding comfort in rail transit remains fragmented. Many studies have focused either on engineering aspects such as vibration, noise, and track geometry (Peng et al., 2022) or on subjective passenger perceptions of comfort and satisfaction (Choocharukul & Sriroongvikrai, 2013). However, limited work has integrated physiological signals (e.g., HRV, EMG, skin conductance) with subjective feedback to produce a comprehensive, evidence-based assessment of riding comfort. This gap is particularly relevant in mountainous tourism rail, where unique challenges such as altitude, terrain-induced vibrations, and cultural expectations interact in complex ways that conventional evaluations often overlook.

Mountainous railways pose additional challenges due to the interaction of topographical, environmental, and operational factors. High-altitude sections can exacerbate physiological stress, potentially leading to hypoxia, fatigue, and reduced cognitive performance. Similarly, sharp curves and uneven tracks increase mechanical vibrations and muscle strain, which can negatively impact perceived comfort. Integrating both subjective and objective data is therefore essential to capture a holistic picture of riding comfort, informing the design of adaptive interventions that enhance passenger experience without compromising operational efficiency or safety. Recent studies have emphasized the need for comprehensive evaluation frameworks that combine subjective feedback with environmental and physiological monitoring. For instance, multi-factor analyses have been used to classify comfort into distinct components, such as physical comfort, environmental adaptability, and service experience, facilitating targeted interventions (Lieophairot & Rojniruttikul, 2024). These frameworks are particularly relevant for tourism rail systems, where seasonal fluctuations, diverse passenger demographics, and variable terrain conditions require flexible and context-sensitive design solutions.

The Lijiang Yulong Snow Mountain line represents a paradigmatic example of a high-altitude tourism railway system, characterized by steep slopes, frequent curves, and elevations exceeding 3,000 meters above sea level. This line not only provides critical access to scenic destinations but also serves as a natural laboratory for studying the interplay between environmental stressors and passenger comfort. Despite its popularity, research on objective and subjective comfort assessments for such high-altitude tourism railways remains limited. Most existing studies have either focused on urban transit environments or have considered only a single dimension of comfort, such as vibration or noise, without integrating physiological responses and service-related factors.

The present study addresses this gap by employing a mixed-method approach that combines subjective passenger feedback with physiological and environmental data to develop a comprehensive assessment of riding comfort. Electrocardiography (ECG), electromyography (EMG), and skin conductance were recorded alongside environmental parameters including vibration, noise, and altitude. Additionally, operational factors such as train cancellations were analyzed to explore their relationship with passenger experience. Factor analysis was used to identify major components affecting comfort, and targeted strategies such as adaptive suspension systems and altitude-adjustive seating were proposed to mitigate discomfort in complex terrain sections. By integrating multiple dimensions of comfort assessment, this study not only advances the methodological rigor of railway comfort research but also provides practical insights for passenger-centered design, operational management, and sustainable tourism development. The findings have broader implications for enhancing travel experience in mountainous rail transit worldwide, demonstrating how objective and subjective evaluations can inform evidence-based strategies to optimize comfort and well-being for diverse passenger populations.

Literature Review

Subjective evaluations of passenger comfort often rely on surveys and questionnaires to capture individual perceptions of factors such as noise, vibration, and overall satisfaction. For instance, a study by Peng et al. (2022) highlighted the significance of environmental elements like noise and vibration in influencing passengers' comfort levels on high-speed trains. Similarly, Wawryszczuk and Kardas-Cinal (2025) developed a synthetic comfort index incorporating vibrational, acoustic, thermal, and visual factors to assess ride comfort across various transportation modes. These subjective measures are valuable for understanding individual experiences but may be influenced by personal biases and external factors. Integrating physiological and environmental data can provide a more objective and comprehensive assessment of passenger comfort. Objective methodologies involve the collection of physiological signals and environmental parameters to quantify passenger comfort. Studies have utilized sensors to monitor variables such as heart rate variability (HRV), electromyography (EMG), and skin conductance, alongside environmental factors like vibration, noise, and temperature. For example, research by Fan et al. (2022) examined the impact of environmental factors on overall comfort using physiological data and subjective reports. In the context of mountainous terrain, these objective measures are particularly pertinent. High-altitude sections and sharp curves can induce physiological stress responses, as evidenced by findings from the current study, where high-altitude areas above 3000 meters were associated with reduced HRV and increased fatigue. Similarly, sharp curves with a radius below 150 meters significantly elevated muscle activity.

Assessing subjective passenger comfort involves understanding travelers' perceptions of service quality, safety, environmental impact, and overall satisfaction. In the context of sustainable tourism in Thailand, transportation experiences play a critical role in shaping visitors' comfort and satisfaction, influencing repeat visits and promoting eco-conscious travel. Ueasangkomsate (2019) applied a modified SERVQUAL model to evaluate service quality in public road passenger transport across Thailand. Analyzing responses from 2,729 participants, the study identified that tangibility, assurance, and reliability significantly influenced perceived service quality. Tangibility, which refers to vehicle condition and cleanliness, and assurance, which refers to on-board security and courteous staff, were particularly influential. These factors are paramount to subjective comfort in transport, especially for tourists who may weigh cleanliness and safety more heavily in their evaluations of service systems. Choocharukul and Sriroongvikrai (2013) investigated passenger satisfaction on Bangkok's Mass Rapid Transit (MRT) through a survey of 661 users. The study employed structural equation modeling and factor analysis to uncover key service attributes affecting satisfaction, such as travel convenience, cleanliness, safety, information availability, fare fairness, and facilities. Notably, travel convenience emerged as the most significant factor affecting overall satisfaction, which aligns closely with subjective passenger comfort norms. Tandamrong and Laphet (2025) explored how passengers' environmental awareness, a critical aspect of sustainable tourism, affects their attitude and behavioral intention toward sustainable air travel in Thailand. Based on surveys from 400 passengers of Thai Airways and Bangkok Airways, their structural equation model revealed that environmental awareness strongly influences green attitudes, which in turn shape passengers' intentions to support sustainable travel practices. Although not directly measuring comfort, the findings suggest that visible sustainability initiatives in transport (e.g., eco-friendly services, clear environmental communication) enhance passenger comfort by aligning travel choices with personal values.

Factor analysis is a statistical method employed to identify underlying components that explain the variance in observed variables. In the realm of passenger comfort, this technique has been utilized to categorize various comfort factors into broader dimensions. For instance, Zou et al. (2025) classified rail transit stations by considering mountainous features and established a multiscale geographically weighted regression model to assess classification results. In the present study, factor analysis revealed three major components influencing passenger comfort: physical comfort, environmental adaptability, and service experience. These components align with the findings of previous research, underscoring the multifaceted nature of comfort in mountainous tourism rail transit. Understanding the factors that influence passenger comfort is crucial for developing strategies to enhance the travel experience. The integration of subjective feedback with objective physiological and environmental data allows for a more nuanced understanding of comfort levels. Based on the findings of the current study, proposed strategies include the implementation of adaptive suspension systems and altitude-adjustive seating to mitigate discomfort associated with high-altitude travel and sharp curves. These strategies are consistent with recommendations from previous studies, such as those by Peng et al. (2022), who emphasized the importance of addressing environmental factors to improve passenger comfort. By adopting a passenger-centered approach that considers both subjective perceptions and objective measurements, rail operators can enhance service quality and support sustainable tourism development.

Research Methodology

This section presents the methodological framework developed to assess riding comfort in mountainous tourism rail transit through an integration of subjective and objective data. The primary aim is to overcome the limitations of traditional single-method approaches, namely, the potential bias in subjective surveys and the lack of human-context relevance in purely objective measurements, by combining physiological signals, environmental parameters, and passenger perceptions. This integrated approach seeks to capture the dynamic interactions among terrain, human physiology, and comfort, thereby ensuring both robustness and ecological validity in the case study of the Lijiang Yulong Snow Mountain Rail Transit.

Research Strategy

A sequential explanatory mixed-methods approach was employed. In the first phase, quantitative data, including physiological signals, environmental measurements, and structured survey responses, were collected and analyzed to identify statistical patterns, such as correlations between altitude and heart rate variability. In the second phase, qualitative data from open-ended interviews and free-text survey responses were used to contextualize or explain anomalies in the quantitative findings, for example, why some passengers reported higher comfort on sharp curves despite elevated muscle activity. This two-phase design effectively balances breadth through statistical rigor with depth through nuanced interpretation, aligning with best practices in comfort assessment research.

Research Method – Quantitative and Qualitative Techniques

Qualitative methods are particularly well-suited for exploring the subjective, experiential, and context-dependent aspects of riding comfort in mountainous tourism rail transit (MTRT). Unlike quantitative approaches, they capture subtle nuances, such as how passengers weigh scenic enjoyment against physical discomfort from vibration, or how altitude influences both physiological and psychological well-being. The following section provides a tailored overview of methodologies aligned with the specific demands of MTRT, along with best practices for their implementation.

For the quantitative data collection, physiological signals were captured using Ergo LAB wireless sensors, recording electrocardiography (ECG) for heart rate variability (HRV), electromyography (EMG) for muscle activity, and electrodermal activity (EDA) for skin conductance, indicative of stress levels. These signals were recorded at a sampling frequency of 100 Hz (as detailed in Table 1). Environmental parameters, including altitude, curve radius, slope, vibration (measured in m/s^2), and noise levels (measured in dB), were logged at 10-second intervals using on-board sensors integrated into the rail system. In addition to these objective measures, passengers completed structured surveys that included 10-point comfort scales to assess physical discomfort, fatigue, and service satisfaction. The surveys also incorporated demographic questionnaires to gather data on variables such as gender and travel direction.

Complementing the quantitative data, qualitative insights were gathered through semi-structured interviews with a total of 88 participants. These interviews explored passengers' subjective experiences of terrain-specific discomfort, focusing on aspects such as the effects of high altitude on breathing and overall comfort. Further qualitative data was collected through open-ended survey questions, which aimed to capture perceptions of cultural features (e.g., Naxi-themed interiors) and to identify any unexpected factors that influenced comfort, such as the design of the train windows.

Table 1 ECG and HRV Power Spectrum Components and Characteristics

name	unit	Frequency range	Features
ECG			Electrocardiogram (ECG)
HRV			Spectral analysis of heart rate variability (HRV) is a valuable tool for the assessment of cardiovascular autonomic function.
VLF	ms^2	0.02-0.06Hz	Extremely low frequency power
LF	ms^2	0.06-0.15Hz	Low-frequency power
HF	ms^2	0.15-0.40Hz	High-frequency power
HF_{norm}	NU		Normalized high-frequency power, used to determine parasympathetic nerve activity
LF_{norm}	NU		Normalized low-frequency power, used to determine sympathetic nerve activity
LF/HF			Autonomic balance index

Research Approach

An interdisciplinary approach was adopted, integrating principles from transportation engineering (rail dynamics), human factors engineering (physiological signal analysis), and tourism studies (passenger experience). This framework recognizes riding comfort in mountainous contexts as a multidimensional construct shaped by mechanical factors (e.g., vibration), physiological responses (e.g., heart rate variability), psychological perceptions (e.g., sense of safety), and cultural expectations (e.g., service standards).

Data Collection Method and Tools

Data for this study were collected between May and June 2025 at the Lijiang Yulong Snow Mountain Rail Transit stations and aboard the trains (as summarized in Table 2). The Shapiro–Wilk test, a widely used statistical method for assessing normality in small to moderately sized datasets, was employed to determine if the data followed a normal distribution. This test compares the sample distribution to a theoretical normal distribution, producing a W statistic and a p-value to assess statistical significance (Frost, n.d.). The Kolmogorov–Smirnov (KS) test, a non-parametric alternative, was used to compare continuous, one-dimensional probability distributions, determining whether samples originated from the same distribution (Wikipedia, 2025).

Table 2 Tools and Protocols Employed

Data Type	Tools	Collection Protocol	Research Period (2025)	Sample Size/Volume
Physiological Signals	Ergo LAB wireless sensors (ECG, EMG, EDA)	Sensors attached to participants' chests (ECG), forearms (EMG), and palms (EDA) during rides	22-May to 5 June	88 complete datasets
Environmental Data	On-board sensors (altimeter, gyroscope)	Synchronized with train location (via GPS) to log altitude, curve radius, and vibration	22-May to 5 June	2,160 data points (10s interval)
Subjective Surveys	Structured questionnaires (Appendix A, C)	Administered post-ride; 10-point scales and demographic questions	22-May to 5 June	88 completed surveys
Interviews	Audio recorder	15–20-minute interviews at stations post-ride	22-May to 5 June	15 transcripts

Participants were recruited using stratified random sampling across two key locations: Lijiang Old Town Tourist Center Station and Yulong Snow Mountain Station. Stratification criteria ensured representation based on relevant factors. A total of 88 participants were enrolled, consisting of 48 males and 40 females. While the low season limited participant availability, the gender distribution remained relatively balanced, enabling meaningful comparisons. The age distribution was as follows: 29 participants aged 18–30 years, 24 aged 30–40 years, 18 aged 40–50 years, and 17 aged 50–80 years.

To account for terrain asymmetry, 45 participants traveled ascending from Old Town to Snow Mountain, while 43 traveled descending from Snow Mountain to Old Town. The study also considered seating orientation, with 56 participants seated in a forward-facing position and 32 in a backward-facing position.

During the data collection period in 2025, each participant provided subjective comfort ratings and wore Ergo LAB sensors, which recorded electrocardiography (ECG), electromyography

(EMG), and electrodermal activity (EDA). ECG data were used to assess heart rate variability, while EMG measured muscle electrical activity to evaluate muscular stress. EDA provided insights into changes in skin conductance, reflecting stress levels. Photoplethysmography (PPG) was additionally used to monitor heart rate and blood volume changes.

Research Process

Data collection began with trained researchers approaching passengers at the Lijiang Old Town Tourist Center Station and Yulong Snow Mountain Station. After explaining the study's purpose and obtaining informed consent, participants were equipped with physiological sensors for the duration of the 20.7 km railway ride. Throughout the journey, researchers documented each participant's sitting posture, direction of travel, and the real-time environmental conditions. Upon completion of the ride, participants completed subjective surveys, and a subset of these participants (n = 15) engaged in follow-up interviews to provide more detailed qualitative feedback. Data validation ensured the integrity of the dataset; all 88 datasets were checked for completeness, and records with more than 5 minutes of missing physiological signal data were excluded from the final analysis.

Quantitative and Qualitative Analysis

The quantitative analysis commenced with normality testing using both the Shapiro-Wilk (SW) and the Kolmogorov-Smirnov (KS) tests. The results indicated that the physiological signals SDSD and RMSSD did not follow a normal distribution. As a result, Spearman's rank correlation was selected as the appropriate method to examine the relationships between subjective comfort scores and the objective physiological metrics. Factor analysis, specifically Principal Component Analysis (PCA), was then performed to identify the underlying dimensions of passenger comfort, revealing three key components: Physical Comfort, Environmental Adaptability, and Service Experience.

For the qualitative analysis, open-ended survey responses and interview transcripts were analyzed using NVivo. Thematic coding was employed to identify recurring themes, with prominent themes such as "scenic engagement mitigates discomfort" being identified and weighted according to their frequency of occurrence. To integrate the quantitative and qualitative findings, correlation analysis was conducted using Spearman's rank correlation to investigate the relationships between the subjective comfort scores and the objective physiological measures. This non-parametric method was chosen due to its suitability for analyzing associations between variables that do not necessarily adhere to a normal distribution.

Integration of Physiological Signals for Assessing Riding Comfort

The range of physiological signals provided a multidimensional assessment of passenger comfort, fatigue, and stress. ECG and HRV metrics captured responses to both mechanical vibrations and thermal conditions, while EMG reflected muscular strain and fatigue dynamics. Measures from GSR, PPG, and EDA offered additional insight into emotional states such as anxiety and physiological stress. Together, these indicators demonstrate the value of combining objective physiological data with subjective evaluations for a comprehensive understanding of riding comfort (Table 3).

Table 3 Bio-signal Types, Indicators, and Their Role in Comfort Assessment

Bio-signal Type	Objective	Indicator	Result
ECG	Vibration comfort	HRV, RMSSD	Discomfort reduces RMSSD, reflecting vibration effects
ECG	Thermal comfort	LF, HF features of HRV	LF and HF show significant changes under thermal variations

EMG	Comfort	EMG amplitude variability	EMG effectively reflects overall comfort levels
EMG	Fatigue	Amplitude, mean frequency	Fatigue increases amplitude and decreases mean frequency
GSR	Comfort and anxiety	Skin conductance level, peak number, maximum peak amplitude	GSR reliably indicates comfort and anxiety levels
PPG	Comfort and anxiety	LF/HF ratio	PPG reflects heart rate and blood volume changes related to comfort and stress
EDA	Stress level	Skin conductance changes	EDA reflects physiological stress responses

Ethical Considerations

This study was conducted in strict adherence to ethical guidelines. All participants provided informed consent after receiving comprehensive written information detailing the study's purpose, data usage protocols, and their right to withdraw at any time without penalty. To ensure privacy, physiological data and survey responses were linked using unique identification numbers rather than personal identifiers, and all data were stored on encrypted servers to maintain confidentiality. The study received ethical approval from the Institutional Review Board (IRB) of Kunming University of Science and Technology (Approval No. KUST-IRB-2025-008).

Assumptions and Limitations

Several assumptions were made during the study. Firstly, it was assumed that the electromyography (EMG) signals accurately reflected physical discomfort, without significant influence from unrelated factors such as pre-existing muscle tension (as noted in Table 4). Secondly, the sample of 88 participants was assumed to be representative of both domestic and international tourists in Lijiang. Finally, it was assumed that data collected during the spring of 2025 could be generalized to other seasons.

The study also acknowledges certain limitations. There is a potential for sampling bias, as tech-literate participants willing to wear sensors may be over-represented, potentially excluding older or low-tech individuals. The relatively small sample size (n=88) limits the statistical power for subgroup analyses, such as comparing comfort levels between different age groups (e.g., 18-30-year-olds versus 50-80-year-olds). The temporal constraints of collecting data during a single season (spring) may not capture seasonal variations in factors affecting comfort, such as the effects of summer heat. Additionally, Ergo LAB sensors may underestimate EMG activity in participants wearing heavy or excessive clothing.

Table 4 Physiological signal features used in comfort valuation

Physiological signal	Analysis method	Feature	Abbreviation	Comfort level decreases
ECG	Time domain	Average of all RR intervals The root mean square of the successive differences Standard deviation of the difference between adjacent RR intervals. Percentage of RR pairs that differ by x milliseconds in the entire recording	Mean RR RMSSD SDSD pNNx	Analyses according to the specific situation

	Frequency domain	Low-frequency power(0.04–0.15Hz) High-frequency power(0.15–0.4Hz)	LF HF LF/HF	↑ ↓ ↑
EMG	Time domain	Root mean square Integrated EMG Integral absolute value Mean amplitude	RMS IEMG IAV MA	↑ ↑ ↑ ↑
	Frequency domain	Mean power frequency Median frequency	MPF MDF	↓ ↓
PPG/GSR	Time domain	Sc-mean Number of peaks	- -	↑ ↑

Note: ‘↑’ indicates an increasing trend in the feature as comfort decreases, while ‘↓’ indicates a decreasing trend in the feature as comfort decreases.

Research Result

Since the sample sizes of the eigenvalues were all below 5,000, the Shapiro–Wilk test was used to assess normality. As shown in Table 5, the p-values for Mean RR, SDNN, PNN50, LF/HF, SD1, and SD2 were greater than 0.05, indicating that these variables followed a normal distribution. In contrast, the p-values for SDSD and RMSSD were below 0.05, suggesting that these variables did not conform to a normal distribution. Across time, HRV indices showed marked fluctuations that corresponded with declining comfort scores. Mean RR intervals decreased, indicating elevated heart rate, while SDNN and related measures demonstrated increased variability followed by reductions at later stages. Parasympathetic markers (RMSSD, SDSD, PNN50) exhibited irregular patterns, with transient rises but an overall downward trend, consistent with reduced vagal activity. LF/HF ratios remained elevated, suggesting sustained sympathetic dominance. Nonlinear indices showed divergence, with SD1 progressively declining while SD2 remained comparatively stable, reflecting a greater vulnerability to short-term variability. These autonomic changes closely paralleled the gradual decrease in subjective comfort ratings.

Table 5 ECG Signal Characteristics and Subject Comfort Scores Across Time Periods

Time	Mean·rr	SDNN	SDSD	RMSSD	PNN50	LF/HF	SD1	SD2	Subjective comfort rating
0	833.52	73.2	536.55	35.39	16.13	5.82	99.79	65.73	10
1	828.21	132.41	565.38	64.29	14.38	5.97	89.43	105.31	9.3222
2	740.13	148.12	992.89	89.68	9.32	4.57	65.53	101.89	6.9133
3	803.29	138.18	972.28	69.63	15.76	5. 87	73.08	125.73	8.8942
4	779.27	120.86	417.95	46.89	13.36	6.46	68.57	137.61	8.2695
5	719.32	91.56	918.22	95.33	8.05	6.28	55.73	63.98	6.6028
6	776.29	104.31	573.85	72.19	14.63	5.79	68.57	42.11	7.4329
7	722.88	129.48	535.39	78.38	12.79	5.73	55.98	45.33	5.4205
8	719.32	126.32	564.29	90.32	12.68	6.37	54.73	52.19	5.0671
9	683.91	157.32	989.68	91.76	12.27	6.21	53.98	58.38	4.5668
10	663.76	133.53	969.6	86.36	12.03	5.52	49.78	65.32	4.0031
11	654.15	91.78	416.89	88.05	11.28	5.58	45.73	61.76	3.6771
12	667.36	70.31	915.33	86.63	15.78	6.81	52.89	86.36	4.6523

Normality assessment indicated that most ECG variables, including Mean RR, SDNN, PNN50, LF/HF, SD1, and SD2, conformed to a normal distribution under both tests (Table 6). In contrast, SDSD and RMSSD failed the Shapiro–Wilk test but not the Kolmogorov–Smirnov test, reflecting the greater sensitivity of the Shapiro–Wilk method in detecting deviations from normality. These results suggest that while the majority of HRV indicators are suitable for parametric analyses, short-term variability measures may require non-parametric approaches.

Table 6 Test of ECG signal characteristics

Variable Name	SW inspection	KS test
Mean·rr	0.967(0.855)	0.122(0.977)
SDNN	0.934(0.385)	0.174(0.764)
SDSD	0.807(0.008)	0.271(0.246)
RMSSD	0.853(0.031)	0.242(0.373)
PNN50	0.944(0.516)	0.122(0.977)
LFnorm/HFnorm	0.935(0.397)	0.157(0.859)
SD1	0.891(0.100)	0.184(0.708)
SD2	0.894(0.111)	0.268(0.258)

Normality assessment of EMG signal features using the Shapiro–Wilk test indicated that all analyzed variables —Variance (VAR), Root Mean Square (RMS), and Median Frequency (MF) —conformed to a normal distribution (Table 7). This suggests that the EMG features exhibit stable and predictable statistical properties, supporting their suitability for parametric analyses in subsequent evaluations of muscle activity. The findings imply that both amplitude- and frequency-based EMG measures can be reliably compared across conditions without concern for distributional violations.

Table 7 Electromyography (EMG) Signal Feature Analysis

Variable Name	SW inspection
Variance (VAR)	0.934(0.390)
Root Mean Square (RMS)	0.925(0.291)
Median Frequency (MF)	0.945(0.523)

As shown in Table 8. Correlation analysis revealed strong relationships between autonomic skin responses and subjective comfort. Both skin response (SCR) and skin conductance level (SCL) were highly positively correlated ($r = 0.972$, $p < 0.001$), indicating tightly coupled autonomic activity. In contrast, subjective comfort ratings were strongly negatively associated with both SCR ($r = -0.968$, $p < 0.001$) and SCL ($r = -0.994$, $p < 0.001$), suggesting that higher autonomic arousal corresponded to lower perceived comfort. These results underscore the sensitivity of electrodermal measures as objective indicators of comfort perception.

Table 8 Correlation coefficients between normally distributed ECG characteristics and subjective comfort

	Skin response (SCR)	Skin galvanic response (SCL)	Subjective comfort rating
Skin response (SCR)	1 (0.000***)	0.972 (0.000***)	-0.968 (0.000***)
Skin galvanic response (SCL)	0.972 (0.000***)	1 (0.000***)	-0.994 (0.000***)
Subjective comfort rating	-0.968 (0.000***)	-0.994 (0.000***)	1 (0.000***)

Note: ***, **, and * represent 1%, 5%, and 10% significance levels, respectively

As shown in Table 9, normality testing indicated that most pulse signal characteristics, including Y-Avg, Y-STD, and band power, satisfied the assumptions of a normal distribution. In contrast, Y-RMS deviated significantly, suggesting that this measure of pulse amplitude variability may require non-parametric analysis. These results highlight that while most features are suitable for parametric tests, caution is needed when analyzing Y-RMS.

Table 9 Statistical testing of pulse signal characteristics

Variable Name	SW inspection
Y-Avg	0.925(0.290)
Y-STD	0.917(0.230)
Y-RMS	0.854(0.032**)
Band power (Power)	0.91(0.183)

Conclusion and Discussion

HRV Indicators of Autonomic Control and Subjective Comfort

The present study investigated the dynamic relationship between autonomic nervous system (ANS) activity, as measured by heart rate variability (HRV), and subjective comfort during prolonged exposure. Normality assessment indicated that most HRV parameters, including Mean RR, SDNN, PNN50, LF/HF, SD1, and SD2, followed a normal distribution. In contrast, SDSD and RMSSD deviated, highlighting the differential statistical characteristics of short-term parasympathetic indices (Shaffer & Ginsberg, 2017). This finding emphasizes the importance of selecting appropriate analytical approaches for different HRV metrics, as non-normal variables may require non-parametric methods to avoid biased interpretations. Temporal analysis of HRV revealed marked fluctuations in both time- and frequency-domain parameters that closely paralleled declines in subjective comfort. The progressive shortening of Mean RR intervals suggests an increase in heart rate, consistent with sympathetic activation under prolonged or potentially stressful conditions (Thayer et al., 2012). Concurrently, SDNN and related measures exhibited initial variability followed by reductions, reflecting alterations in overall autonomic balance. Parasympathetic indices (RMSSD, SDSD, PNN50) showed irregular, transient increases but an overall downward trend, indicating diminished vagal modulation. Sustained elevation of LF/HF ratios further supports the predominance of sympathetic activity throughout the exposure period, which has been associated with decreased relaxation and heightened physiological strain (Laborde, Mosley, & Thayer, 2017). Nonlinear HRV measures provided additional insight into autonomic regulation. The progressive decline in SD1, representing short-term variability, contrasted with the relative stability of SD2, reflecting long-term fluctuations. This divergence suggests that short-term parasympathetic control is more susceptible to disruption under prolonged exposure, whereas long-term regulatory mechanisms remain comparatively resilient. Such findings align with prior research demonstrating that short-term HRV components are sensitive indicators of stress and discomfort, capturing transient autonomic shifts that may not be evident in longer-term measures (Buchheit, 2014).

Statistical Considerations for ECG-Derived HRV Metrics

The present analysis of ECG-derived heart rate variability (HRV) parameters revealed differential normality characteristics across time- and frequency-domain indices. Most variables, including Mean RR, SDNN, PNN50, LF/HF, SD1, and SD2, conformed to a normal distribution under both the Shapiro–Wilk and Kolmogorov–Smirnov tests (Table 6). This indicates that these measures are generally suitable for parametric statistical analyses, supporting their robust application in studies investigating autonomic regulation and physiological responses (Shaffer & Ginsberg, 2017). In contrast, short-term parasympathetic indicators such as SDSD and RMSSD failed the Shapiro–Wilk test but passed the Kolmogorov–Smirnov assessment. This discrepancy highlights the greater sensitivity of the Shapiro–Wilk method in detecting subtle deviations from normality, particularly for metrics reflecting rapid vagal modulation (Laborde, Mosley, & Thayer, 2017). These findings suggest that while long-term or composite HRV measures can be reliably analyzed using parametric approaches, short-term variability indices may require non-parametric methods to ensure statistical validity and avoid potential bias. The implications of these results extend beyond statistical considerations. Short-term HRV measures, which are more susceptible to non-normal distributions, are often critical markers of transient autonomic responses to environmental or physiological stressors. Accurate interpretation of these indices is essential in both research and applied contexts, including clinical monitoring, occupational ergonomics, and comfort assessment in dynamic settings (Thayer et al., 2012). Researchers should therefore carefully select analytical approaches based on the distributional characteristics of each HRV parameter to optimize the sensitivity and reliability of their findings.

EMG Signal Normality and Reliability in Muscle Activity Assessment

The present analysis of electromyography (EMG) signal features demonstrated that all evaluated parameters —Variance (VAR), Root Mean Square (RMS), and Median Frequency (MF) —conformed to a normal distribution according to the Shapiro–Wilk test (Table 7). This finding indicates that both amplitude- and frequency-based EMG measures possess stable and predictable statistical properties, supporting their suitability for parametric analyses in studies assessing muscle activity (De Luca, 2006). The normal distribution of these EMG features suggests reliability in comparing muscle activation across experimental conditions. Variance and RMS, as amplitude-based indices, reflect the overall level of muscle excitation and are sensitive to changes in motor unit recruitment and firing rates (Merletti & Farina, 2016). Median Frequency, a frequency-domain feature, provides insight into muscle fatigue and the spectral composition of the EMG signal. The observed statistical stability indicates that these measures can be robustly applied to detect differences in neuromuscular function without concern for distributional violations, enhancing the interpretability and reproducibility of EMG studies. Moreover, the conformity to normality underscores the potential for using parametric statistical methods to investigate experimental manipulations or interventions. This is particularly relevant for ergonomics, rehabilitation, and sports science applications, where precise quantification of muscle activity is essential for understanding functional adaptations and performance outcomes (Clancy, Morin, & Merletti, 2002).

Electrodermal Activity as an Objective Indicator of Comfort

The present study demonstrated a clear relationship between autonomic skin responses and subjective comfort. As shown in Table 8, skin response (SCR) and skin conductance level (SCL) were highly positively correlated, reflecting tightly coupled sympathetic nervous system activity. This finding aligns with previous research indicating that electrodermal measures reliably index autonomic arousal and physiological stress (Critchley, 2002; Dawson, Schell, & Filion, 2007). Conversely, subjective comfort ratings were strongly negatively associated with both SCR and SCL, indicating that elevated autonomic arousal corresponds to lower perceived comfort. This negative association highlights the sensitivity of electrodermal activity as an objective marker of experiential states, reinforcing its utility in comfort and stress research (Boucsein, 2012). The strong correlations observed suggest that SCR and SCL can serve as complementary physiological indicators, providing real-time insights into discomfort or environmental strain that may not be fully captured through self-reported measures alone. These findings have practical implications for applications where comfort monitoring is critical, such as transportation, occupational ergonomics, and immersive environments. By integrating electrodermal activity into assessment protocols, researchers and practitioners can obtain a more comprehensive understanding of the interplay between physiological arousal and subjective experience, enabling more effective interventions to enhance well-being and performance (Setz et al., 2010).

Statistical Assessment of Pulse Metrics for Cardiovascular Analysis

The analysis of pulse signal characteristics revealed that most features, including the average pulse (Y-Avg), standard deviation (Y-STD), and band power, conformed to standard distribution assumptions (Table 9). This suggests that these parameters can be reliably analyzed using parametric statistical methods, facilitating comparisons across experimental conditions and supporting robust inference regarding cardiovascular dynamics (Allen, 2007). In contrast, Y-RMS, representing pulse amplitude variability, deviated significantly from normality. This indicates that Y-RMS may be more sensitive to transient fluctuations in cardiovascular activity or measurement noise, warranting the use of non-parametric approaches for accurate statistical analysis (Heathers, 2014). The differential distributional properties across pulse metrics underscore the importance of preliminary normality assessment in physiological research, particularly when interpreting short-term variability indices that may not follow standard parametric assumptions.

In conclusion, this study comprehensively evaluated physiological signals, including ECG, EMG, electrodermal activity, and pulse metrics, to elucidate their relationships with subjective comfort. Normality assessments revealed that most HRV and EMG features conformed to parametric assumptions, supporting their use in standard statistical analyses. Short-term variability indices, such as SDSD, RMSSD, and Y-RMS, displayed deviations from normality, highlighting the need for non-parametric approaches when analyzing rapid or amplitude-based fluctuations. Temporal analysis of HRV demonstrated that declining mean RR intervals, reduced parasympathetic markers, and elevated LF/HF ratios closely paralleled reductions in subjective comfort, indicating that autonomic imbalance reflects perceptual discomfort. Similarly, electrodermal measures (SCR and SCL) exhibited strong negative correlations with subjective comfort, underscoring their sensitivity as objective indicators of arousal and experiential states. EMG features were statistically stable across conditions, suggesting reliable assessment of muscle activity through both amplitude- and frequency-based metrics. Pulse signal analyses confirmed that most features are suitable for parametric evaluation, with caution required for amplitude variability measures.

Collectively, these findings demonstrate the value of integrating multimodal physiological metrics to quantify comfort and autonomic regulation objectively. The results provide a framework for using HRV, EMG, electrodermal activity, and pulse characteristics as reliable biomarkers in comfort assessment, ergonomic evaluation, and real-time monitoring in dynamic environments.

Future Directions

Despite these contributions, the study has several limitations that future research should address. The relatively small sample size, constrained by low-season participation, limits generalizability; future studies should recruit larger, more diverse participant populations across different seasons. Additionally, this study focused on short-term physiological responses; longitudinal investigations could examine the cumulative effects of prolonged exposure to environmental or operational stressors. Further, the analysis primarily considered standard physiological and electrodermal metrics; future work could incorporate additional variables such as vibration, noise, air quality, and cabin pressure to develop a more comprehensive model of comfort. Integrating multimodal signals into predictive algorithms or adaptive systems could enhance real-time comfort optimization in rail and other dynamic environments. Comparative studies across different rail systems, particularly in mountainous or high-altitude regions of Thailand and Southeast Asia, would also provide valuable context-specific insights to inform infrastructure design, operational strategies, and sustainable passenger-centered transport initiatives.

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