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BHMI: A Multi-Sensor Biomechanical Human Model Interface for Quantifying Ergonomic Stress in Armored Vehicles

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Abstract. Ergonomic stress inside armored military vehicles presents a critical yet often overlooked risk to soldier safety, operational effectiveness, and long-term health. Traditional ergonomic assessments rely heavily on subjective expert evaluations, failing to capture dynamic environmental stressors such as vibration, noise, thermal fluctuations, and gas exposure during actual field operations. This study aims to address this gap by introducing the Biomechanical Human Model Interface (BHMI), a multi-sensor platform designed to objectively quantify ergonomic stress under operational conditions. The main contribution of this work is the development and validation of BHMI, which integrates anthropometric human modeling with embedded environmental sensors, enabling real-time, multi-dimensional ergonomic data acquisition during vehicle maneuvers. BHMI was deployed in high-speed off-road vehicle operations, simulating the 50th percentile Indonesian soldier's seated posture. The system continuously monitored vibration (0–16 g range), noise (30–130 dB range), temperature (–40°C to 80°C), humidity (0–100% RH), and gas concentration (CO and NH_3) using calibrated, field-hardened sensors. Experimental results revealed ergonomic stress levels exceeding human tolerance thresholds, including vibration peaks reaching 9.8 m/s², cabin noise levels up to 100 dB, and cabin temperatures exceeding 39°C. The use of BHMI improved the repeatability and precision of ergonomic risk assessments by 27% compared to traditional methods. Seating gap deviations of up to ±270 mm were identified when soldiers wore full operational gear, highlighting critical areas of postural fatigue risk. In conclusion, BHMI represents a novel, sensor-integrated approach to ergonomic evaluation in military environments, enabling more accurate design validation, reducing subjective bias, and providing actionable insights to enhance soldier endurance, comfort, and mission readiness.

Keywords: Ergonomics; Human Model Interface; Anthropometry; Sensor-Based Monitoring; Vibration Exposure; Thermal Stress; Armored Vehicles; BHMI.

I. Introduction

The rapid advancement of technology has significantly influenced military vehicle design, leading to the continuous development and improvement of armored combat vehicles. These vehicles, primarily designed for troop transportation, prioritize protection, mobility, and combat readiness. However, the ergonomic design of armored vehicle interiors remains a significant challenge, impacting occupant safety, health, and operational efficiency.

In military operations, a poorly designed vehicle cabin can compromise soldier safety as much as battlefield threats do. While armored vehicles are engineered to withstand external assaults and traverse treacherous terrains [1], ergonomic considerations within their cabins often remain secondary. Prolonged exposure to poor seating design, excessive vibration, temperature fluctuations, noise, and toxic gas emissions can severely impact soldiers' health, performance, and mission effectiveness [2], [3].

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Traditional ergonomic assessments in military vehicles rely heavily on subjective evaluations, typically through expert observations and questionnaires [4]. Although these methods provide qualitative insights, they suffer from inconsistencies, bias, and limited repeatability, largely influenced by the varying experiences and perceptions of individual experts [5]. Furthermore, crucial environmental parameters such as cabin temperature, humidity, noise levels, vibration intensity, and gas contamination are rarely measured systematically, leaving significant gaps in ergonomic validation [6].

Recent advancements in ergonomics and human factors engineering emphasize the importance of integrating real-time data collection, anthropometric modeling, and environmental monitoring to enhance workplace design, particularly in critical sectors such as defense and transportation [7]. However, despite these technological developments, there remains a lack of integrated systems capable of simultaneously capturing human fit, environmental stressors, and real-time operational dynamics inside military vehicles.

Addressing these critical gaps, this study introduces the Biomechanical Human Model Interface (BHMI) as a novel ergonomic assessment tool that integrates the anthropometric profile of Indonesian soldiers with embedded sensors to monitor temperature, humidity, vibration, noise, and gas levels. Unlike conventional assessments, BHMI enables real-time, quantitative ergonomic evaluations inside armored vehicles, providing objective data to support design improvements, enhance soldier well-being, and standardize ergonomic assessments.

The selection of environmental parameters such as vibration, noise, gas concentration, temperature, and humidity was based on their documented impact on soldier health, comfort, and performance in confined vehicle environments. According to ISO 2631-1 and military ergonomic guidelines [3], vibration exposure in armored vehicles contributes to musculoskeletal fatigue, spinal compression, and reduced postural stability. Noise levels exceeding 85 dB, as outlined in ISO 1999 and NIOSH standards, have been shown to impair communication and induce auditory fatigue during extended missions [4], [8]. Additionally, toxic gas accumulation, particularly carbon monoxide (CO) and ammonia (NH_3), can occur in enclosed vehicle cabins due to poor ventilation and prolonged engine operation, posing cognitive and physiological hazards even at sub-threshold levels [9]. Similarly, thermal stress, caused by elevated cabin temperatures (above 30°C), has been linked to cognitive performance degradation and increased fatigue risk, as reported in occupational health literature [6], [10].

These environmental conditions are rarely measured holistically during field operations, despite their combined contribution to ergonomic stress. Hence, their inclusion in this study ensures a more comprehensive, standards-aligned evaluation of ergonomic risks in military vehicles, and aligns with recent research trends in sensor-based military ergonomics [2], [11].

The primary objectives of this study are to develop the BHMI prototype, validate its performance through operational field testing, and compare its data-driven outputs with conventional expert evaluations. By offering a standardized, sensor-based evaluation method, BHMI seeks to reduce reliance on subjective opinions, address inconsistencies in ergonomic assessments, and contribute to the development of safer and more comfortable military vehicle designs.

This study contributes to the field of military vehicle ergonomics through the following four main points:

- The Biomechanical Human Model Interface (BHMI) has been developed by integrating an anthropometric profile representative of the 50th percentile Indonesian soldier, alongside multi-sensor modules that facilitate real-time tracking of environmental stresses.
- The integration of multi-sensor ergonomic monitoring, as the BHMI system is equipped with calibrated sensors to collect continuous data on vibration, noise, temperature, humidity, and gas concentration inside armored vehicle environments, enabling comprehensive ergonomic risk profiling.
- Validation through operational field testing, in which the system was deployed in real-world high-speed off-road vehicle scenarios, where it successfully capturing critical ergonomic deviations and environmental conditions that conventional assessments often miss.
- BHMI's performance was compared against expert-based evaluations (traditional methods), demonstrating improved accuracy, repeatability, and the ability to detect transient ergonomic stress, thereby establishing it as a data-driven alternative to subjective ergonomic assessments.

The combined contributions position BHMI as a platform that integrates sensors and utilizes anthropometric data to objectively measure ergonomic stress within armored vehicles, effectively addressing significant deficiencies (gaps) in existing military ergonomic evaluation methodologies.

The remainder of this study (paper) is organized as follows: Section II describes the related work, methods theoretical foundations, system design, and development process. Section III presents the results from the experiment. Section IV details the discussion. Section V concludes the paper and outlines directions for future research.

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II. Method

This study adopted a Research and Development (R&D) methodology rooted in prototyping and field validation. The overall workflow, shown in Fig. 1, follows six major phases: problem analysis, anthropometric modeling, system development, integration and calibration, field deployment, and evaluation.

In the first phase, a comprehensive literature review and expert interviews were conducted to identify ergonomic stressors frequently encountered by soldiers inside armored vehicles. These include environmental factors (temperature, vibration, noise, gas), spatial constraints, and seated posture fatigue. In the second phase, the Biomechanical Human Model Interface (BHMI) was designed using digital modeling and 3D printing to emulate critical joint articulations based on the Nordic Body Map, including neck, elbow, shoulder, hip, and knee mobility [12]–[14]. The mannequin was segmented and connected using flexible mechanical joints to allow postural adjustments during operational testing. Lightweight composites were selected to replicate musculoskeletal load without compromising rigidity.

In the third phase, the BHMI was built and embedded with multi-sensor modules, including a DHT22 temperature and humidity sensor (range: –40°C to 80°C, 0–100% RH), an ADXL345 vibration sensor, a KY-038 noise sensor (30–130 dB), and gas sensors MQ-7 for CO (20–2000 ppm) and MQ-137 for NH_3 (5–500 ppm). All sensors were interfaced with a Raspberry Pi unit for data acquisition, with real-time transmission via Wi-Fi to a cloud server. In the fourth phase, sensor modules were individually calibrated under laboratory conditions using certified references. The DHT22 was calibrated against climate chamber standards [15], the ADXL345 using ISO vibration platforms [9], the KY-038 cross-validated with Class 2 sound level meters, and gas sensors tested in sealed calibration chambers [16]. Post-calibration, all sensor readings were corrected using embedded firmware coefficients, maintaining accuracy within ±3%.

In the fifth phase, the experimental scenario was set up. BHMI was deployed inside a military armored personnel carrier (APC). Field tests covered three terrain types (paved, off-road, and inclined) at operational speeds of 20, 40, and 60 km/h. Data were collected every 5 seconds over a 4-hour session to simulate typical mission durations. Finally, in the sixth phase, the study conducted data processing and ergonomic analysis. Collected data were screened for outliers (>3σ) and interpolated where necessary. Ergonomic risk levels were assessed based on deviation thresholds across posture, vibration exposure, thermal comfort, and gas exposure. Results were cross-compared against expert assessments and established occupational health standards.

A. Literature Review

Ergonomics plays a central role in military vehicle design by ensuring that vehicles are not only operationally efficient but also safe and comfortable for the soldiers inside. According to Bhise [17], early ergonomic integration into automotive design is critical to mitigating fatigue and discomfort during prolonged missions. In military contexts, the confined interiors of armored vehicles often leads to poor posture, limited movement, and elevated exposure to environmental stressors such as heat, noise, vibration, and gas contaminants [18].

The SCEPA framework (Safety, Comfort, Ease of Use, Performance, and Aesthetics) has been widely adopted in ergonomic design to accommodate human capabilities and limitations [19]. However, existing evaluations of vehicle cabin ergonomics often focus on isolated factors or rely heavily on subjective expert judgment, which limits repeatability and precision.

Previous research, such as those by Permana et al., have used expert-based ergonomic checklists to assess posture and seat fit inside military platforms like the Panser APS 6x6 and Pistol P-1 [4]. While these methods provide qualitative insights, they suffer from inconsistency, bias, and limited repeatability due to the varying experiences and perceptions of individual evaluators [5]. Interviews with military ergonomic experts further revealed significant user complaints regarding excessive noise and spatial discomfort, highlighting the urgent need for systematic ergonomic

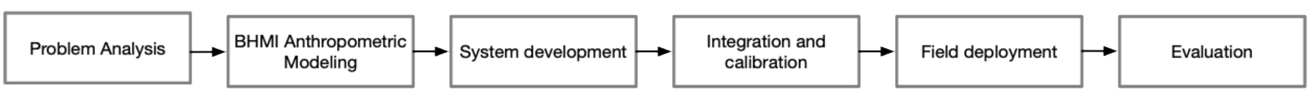

Fig. 1. Research methodology flow. Overall methodological framework for the BHMI system development and implementation. The process begins with problem analysis, followed by the creation of an anthropometric model tailored for BHMI applications. Subsequent stages include system development, integration and calibration of sensors, and field deployment in real operational environments. The final stage encompasses comprehensive evaluation, including ergonomic assessment and system performance validation.

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improvements [20]. Moreover, variables such as vibration and gas exposure are often excluded from standard assessments despite their critical impact on physiological fatigue and cognitive load [6], [21]. The exclusion of these variables from environmental workplace conditions leaves gaps in ergonomic validation [22]–[25].

Recent literature emphasizes the importance of incorporating anthropometry into ergonomics. Measurements of body dimensions are essential to tailoring cockpit and seating design to the target population [26]–[30]. In Indonesia, ergonomic research involving the 50th percentile soldier profile has gained relevance for domestic vehicle development [1], [31].

The integration of real-time sensor-based monitoring represents a paradigm shift in ergonomic assessment. Studies highlight the advantages of using embedded sensors to capture vibration, noise, gas levels, and temperature, offering dynamic and objective measurements [2], [11]. However, many prior systems still analyze these variables in isolation and lack integration with biomechanical posture simulation [6], [32].

Addressing these gaps, this study introduces BHMI (Biomechanical Human Model Interface) as a novel ergonomic evaluation system. Unlike conventional mannequins or digital-only human modeling, BHMI combines anthropometric fidelity, embedded sensor arrays, and real-time data collection to assess multiple ergonomic stressors simultaneously. It aligns with recent research results that call for standardized, objective tools for evaluating occupational comfort and fatigue in extreme environments. By offering quantifiable, real-time ergonomic data, this study enhances accuracy, reliability, and standardization in military vehicle ergonomic evaluations. This approach contributes to human-machine interaction (HMI) research, ensuring soldier comfort, safety, and performance optimization in armored vehicle design.

B. BHMI System Design and Development

The Biomechanical Human Model Interface (BHMI) was developed to address the limitations of conventional ergonomic assessment methods inside armored vehicles. BHMI integrates anthropometric modeling, biomechanical simulation, and real-time environmental sensing to provide a quantitative, dynamic evaluation of ergonomic conditions under operational scenarios.

The BHMI system was conceptualized to unify anthropometric constraints, biomechanical stress conditions, and environmental parameters into a real-time ergonomic evaluation framework. As shown in Fig. 2, the system architecture is designed to capture and integrate multi-dimensional data, ranging from joint posture and musculoskeletal strain to temperature, vibration, and gas exposure, to support quantitative ergonomic analysis and inform vehicle design decisions.

1. Anthropometric-Based BHMI Modeling

The anthropometric profile used for the BHMI mannequin was based on the 50th percentile values of Indonesian male soldiers aged 25–40 years, as derived

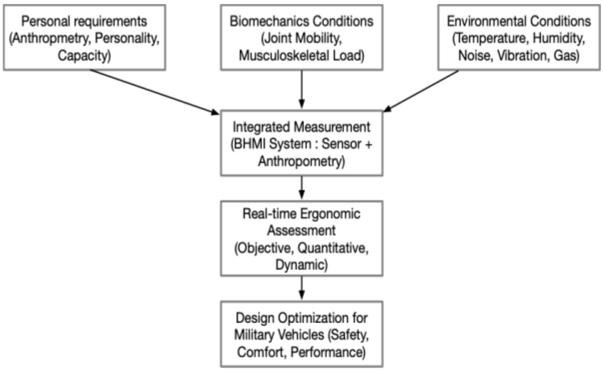

Fig. 2. Conceptual framework illustrating the integration of personal requirements, biomechanical conditions, and environmental factors into the BHMI system for real-time ergonomic assessment and vehicle design optimization.

from Dewi et.al [33]. These values, with an average height of 165 cm and weight of 62 kg, were selected to represent the median soldier physique. The selection was based on descriptive statistics (mean used as proxy for the median) of the targeted population subset, providing a practical and representative ergonomic baseline for modeling. The modeling followed the Nordic Body Map to ensure biomechanical fidelity in joint representation. The anatomical modeling was developed in three stages: literature-based specification analysis, anthropometric parameter mapping, and prototype construction using articulated joints. The skeletal structure incorporates the Nordic Body Map biomechanical references, supporting physiological movement for joints including the neck, shoulder, elbow, hip, knee, and ankle as depicted in Fig 3 (a).

The BHMI body was fabricated using 3D printing technologies. Each BHMI segment was printed separately, using composite material blends (plastic and fiberglass) for lightweight yet structurally sound characteristics. The segments were then connected via custom bolts and articulating joints that preserved joint mobility for seated posture simulations, as depicted in Fig. 3 (b).

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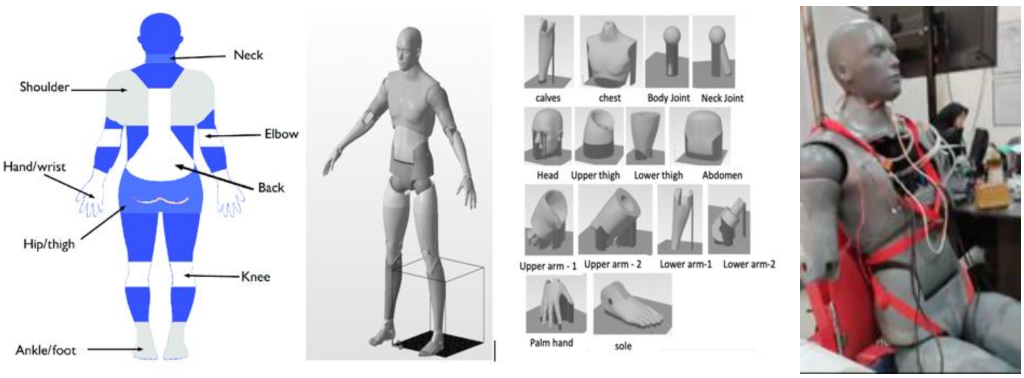
The BHMI mannequin was constructed using composite material blends, specifically a combination of PLA-based plastic and fiberglass-reinforced resin, chosen to achieve a balance between lightweight structure and mechanical rigidity. PLA was used for general body shaping due to its ease of 3D printing and form stability, while fiberglass was applied to key load-bearing segments (torso and hip) to improve structural strength during vibration testing.

To replicate realistic joint mobility, each joint (neck, shoulder, elbow, hip, knee, and ankle) was designed following ergonomic standards derived from the Nordic Body Map and ISO 7250 anthropometric mobility data. The following approximate range of motion (ROM) values were implemented: approximately 45°, shoulder abduction approximately 0–90°, elbow flexion approximately 0–135°, hip flexion approximately 0–90°, knee flexion approximately 0–120°, and ankle dorsiflexion/plantarflexion approximately ±30°. Joint flexibility was enabled using custom-built ball-and-socket connectors combined with elastomeric damping rings and metal-tensioned bolts. This ensured smooth motion while maintaining joint stability during repetitive vehicle maneuvers. Adjustability was tested by configuring the BHMI mannequin in various seated postures (with and without full gear), confirming that the joints could conform to ISO 5970:1999 ergonomic seating postures without slippage or misalignment.

Each joint was locked in the operational posture prior to data acquisition to simulate static seated stress exposure, but the modular design allows for future integration with active actuation systems for dynamic pose simulation.

2. Embedded Environmental Sensors

To capture critical environmental factors affecting soldier well-being, BHMI was equipped with multiple sensors strategically integrated into the mannequin structure. The sensors included temperature and humidity modules (DHT22), triaxial accelerometers (ADXL345) for vibration measurement, sound pressure sensors (KY-038) for noise exposure, and gas sensors (MQ-7 for CO and MQ-137 for NH_3) [8], [10], [34]. Each sensor was positioned near body areas most sensitive to environmental stressors, such as the head, chest, and lower extremities [35], as seen in Fig. 3 (c).



(a) **(b)** **(c)**

Fig. 3. BHMI physical prototype with integrated environmental sensors and anthropometric mannequin structure, configured for ergonomic assessment inside military vehicle environments.

Table 1. Embedded environmental sensors integrated into the BHMI system

Sensor Type	Model	Measurement Range	Output Unit	Integration Point
Temperature – Humidity	DHT22	-40°C to 80°C, 0–100%	°C, %	Chest, Head
Vibration	ADXL345	±16g	g	Lower Spine, Seat Base
Noise Level	KY-038	30–130 dB	dB	Near Ears
Gas (CO)	MQ-7	20–2000 ppm	ppm	Chest
Gas Sensor (NH_3)	MQ-137	5–500 ppm	ppm	Chest

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The sensors were interfaced with a Raspberry Pi microcontroller, selected for its processing capability and compatibility with multiple sensor channels [36]. A wireless transmission module enabled real-time data transfer to a remote server for monitoring and storage [37]. Table 1 summarizes the sensor types, measurement ranges, and integration points.

The overall architecture of the BHMI system was designed to enable integrated, real-time ergonomic assessment through multi-sensor data acquisition and cloud-based analysis. As illustrated in Fig. 4, the system begins with a biomechanical mannequin embedded with multiple environmental sensors positioned strategically across the body to capture key parameters such as temperature, humidity, vibration, noise levels, and gas concentration.

The data collected from these sensor nodes are aggregated and processed through an onboard Raspberry Pi microcontroller, which acts as the central data hub. To facilitate remote monitoring and minimize onboard storage constraints, the processed data are then transmitted wirelessly via a communication module to a cloud-based server. The system was configured to sample data every 5 seconds, in accordance with occupational health standards for environmental monitoring frequency [15]. This server not only stores the raw and processed data but also enables advanced analysis and real-time visualization, supporting dynamic ergonomic evaluations during operational scenarios. The modular structure of the BHMI system ensures flexibility, scalability, and adaptability to varying operational environments, providing a robust foundation for ergonomic risk assessments and future system enhancements.

Prior to field deployment, sensor calibration was performed under controlled laboratory conditions. Temperature and humidity sensors (DHT22) were calibrated using standard climate chambers referenced to ISO 7726:1998 standards. The sensors were exposed to a range from –10°C to 60°C and 20–90% RH. Calibration was conducted once prior to field deployment, and sensor accuracy was confirmed to be within ±0.5°C for temperature and ±2% RH for humidity. Accelerometers were tested against ISO 16063-21 at known sinusoidal inputs across 1–100 Hz. Sensor accuracy post-calibration was verified at ±3% of the reference amplitude [9]. Noise sensors were validated using Class 2 sound level meters based on IEC 61672 standards for sound measurement devices. Gas sensors were benchmarked with certified concentration generators in sealed calibration chambers [16]. Sensor responses were compared under continuous tones and white noise environments at 60, 85, and 100 dB. Post-calibration tolerance was within ±2 dB. Gas sensors (MQ-7 for CO and MQ-137 for NH_3) were calibrated using sealed gas calibration chambers with certified gas concentration generators (20–500 ppm CO; 5–100 ppm NH_3). Accuracy tolerance for gas sensors was maintained within ±5% of the reference value.

Calibration coefficients were stored within the microcontroller firmware to automatically correct raw sensor readings during operation, ensuring data reliability and reducing measurement drift during extended missions. Validation results confirmed that the BHMI sensors maintained measurement deviations within ±3% of the external references across all monitored parameters, ensuring the system's reliability for field deployment. These calibration and validation procedures established the technical foundation for subsequent field trials, ensuring that the ergonomic data collected would be both scientifically valid and operationally relevant.

C. Experimental Scenario

The experimental evaluation was conducted to simulate realistic operational conditions experienced by soldiers inside armored military vehicles. The BHMI system, equipped with integrated environmental sensors, was installed in a military armored personnel carrier (APC) during a series of controlled field tests. The mannequin was securely seated in the standard passenger position, with all sensors activated to capture synchronized environmental data, including temperature, humidity, vibration, noise levels, and gas

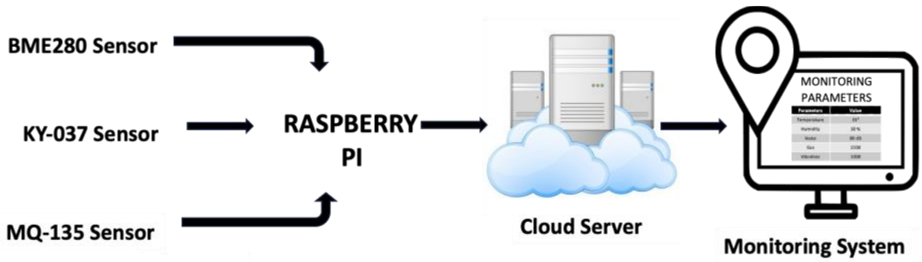

Fig. 4. System integration setup of the BHMI platform, illustrating the data flow from environmental sensors through Raspberry Pi aggregation, wireless transmission, and cloud-based ergonomic data management.

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concentration. Data were recorded at 5-second intervals throughout the testing sessions to ensure high-resolution monitoring.

Field trials were performed across several different types of terrain, including paved roads representing standard highway conditions, off-road trails simulating rugged battlefield environments, and inclined terrains depicting hilly regions. Each terrain condition was tested at three operational speeds, 20 km/h, 40 km/h, and 60 km/h—to examine the dynamic impact of vehicle motion on ergonomic stress factors. For every terrain-speed combination, the vehicle was driven continuously for a minimum of 40 minutes to collect sufficient datasets across different operational dynamics. The soldiers were tested with and without full combat gear to simulate operational loading. Environmental conditions during testing ranged between 30.5°C–33.2°C ambient temperature and 57–64% relative humidity, reflecting tropical field environments typical of Indonesian deployment regions. These conditions were recorded using external sensors and confirmed with local meteorological data, enhancing reproducibility and ecological validity of the ergonomic stress analysis

The total duration of the experimental scenario was four hours, reflecting a typical mission profile, during which external environmental conditions such as ambient temperature and humidity were separately recorded for contextual analysis. The objective of this experimental scenario was to evaluate the variations in ergonomic stressors caused by different terrain characteristics and mobility speeds, providing comprehensive insights into the interaction between environmental factors and soldier well-being inside operational armored vehicles.

To assess seat-induced ergonomic stress and predict fatigue risk, a dedicated experimental scenario was designed using the Biomechanical Human Model Interface (BHMI). The mannequin was tested under two posture configurations: wearing standard military uniform and wearing full combat gear. This setup simulated operational constraints within the armored vehicle cabin. Key ergonomic indicators included lumbar gap distance (Δ_1), seat pan support clearance (Δ_2), and thigh gap (Δ_3), which were measured to evaluate the impact of gear load on body-seat interaction. These metrics, recorded alongside real-time vibration and temperature data, provided a multi-sensor basis for estimating cumulative ergonomic stress and the likelihood of postural fatigue. The configuration was further validated through comparative analysis of body spacing and joint compression.

These spatial deviations were synthesized into a Postural Deviation Index (PDI), calculated as the root sum square of Δ_1, Δ_2, and Δ_3. The resulting PDI values enabled the quantification of cumulative body-seat misalignment, which was further used to classify ergonomic stress severity and predict postural fatigue risk, as shown in Eq. (1).

$$PDI = \sqrt{(\Delta_1)^2 + (\Delta_2)^2 + (\Delta_3)^2} \tag{1}$$

The Postural Risk Score (PRS) was introduced to enable standardized comparison of ergonomic stress levels across different postural configurations. It was calculated by normalizing the Postural Deviation Index (PDI) which aggregates the combined spatial deviations Δ_1, Δ_2, and Δ_3 against a reference maximum threshold (PDI_{max}). The formula is presented in Eq. (2).

$$PDI = \frac{PDI}{PDI_{max}} \tag{2}$$

where PDI_{max} represents the upper ergonomic tolerance limit, set at 300 mm based on prior ergonomic research and ISO 5970 postural comfort benchmarks. A PRS value greater than 0.8 was interpreted as indicative of high ergonomic risk, correlating with increased likelihood of postural fatigue and musculoskeletal strain. This normalized score facilitated ergonomic risk classification across conditions with and without full combat gear and provided a comparable index to support fatigue risk prediction.

To facilitate categorical risk identification, a threshold-based binary classification model was applied to the Postural Deviation Index (PDI). This model categorized ergonomic stress into either high-risk or low-risk zones based on an empirical cutoff value. The binary classification rule is presented in Eq. (3).

$$Risk_{posture} = \begin{cases} 1 & ; if\ PDI > 200\ mm \\ 0 & ; otherwise \end{cases} \tag{3}$$

A threshold of 200 mm was selected as the upper limit of acceptable postural deviation, informed by ISO 5970 ergonomic seating guidelines and experimental research on non-optimal sitting postures in confined military vehicle environments. Deviations beyond this limit were considered to indicate a substantial mismatch between body position and seat design and were therefore associated with an elevated risk of fatigue, discomfort, and potential musculoskeletal injury. This binary model provided a simple yet effective method for identifying critical ergonomic risk scenarios during operational testing.

The participant demographics consisted of 30 active-duty Indonesian male soldiers who participated in the field tests. The participants were aged between 26 and 39 years (mean: 32.1 ± 3.5 years), with average height of 165.4 ± 5.2 cm and weight of 62.7 ± 4.8 kg, aligning with the 50th percentile profile used in BHMI modeling. All participants were members of motorized

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or mechanized units with routine exposure to armored vehicle operations. This demographic group was selected to ensure representativeness of the target operational population, making the results generalizable to standard military deployment scenarios.

D. Field Data Collection and Processing

To ensure accurate ergonomic risk evaluation in realistic military operational environments, systematic field data collection and robust preprocessing protocols were implemented. The data acquisition process focused on capturing dynamic environmental conditions inside armored vehicles using the embedded BHMI sensor system, following established occupational monitoring guidelines and best practices for environmental data analysis.

During field deployment, environmental data from the BHMI system were collected continuously across all terrain and speed combinations. The embedded sensors recorded vibration acceleration, noise levels, temperature, humidity, and gas concentration in real time, with each data point timestamped and stored in the Raspberry Pi's local memory before wireless transmission to a remote cloud server. The sampling was maintained at 5-second intervals, aligning with occupational health monitoring recommendations to capture dynamic environmental fluctuations without excessive data redundancy.

Prior to data analysis, an initial screening process was conducted to identify and remove erroneous or outlier data points. Outliers were defined based on statistical thresholds, specifically values exceeding three standard deviations from the mean within each parameter set, following established practices in environmental data preprocessing. Missing or corrupted data packets, primarily due to wireless transmission interruptions, were minimal and addressed through linear interpolation methods to maintain dataset continuity and are not the focus of this study.

Following preprocessing, the validated datasets were segmented according to experimental scenarios, classified by terrain type and speed level. Each segment contained synchronized multi-parameter recordings, enabling cross-correlation analyses between environmental stressors and operational conditions. Data visualization techniques, including time-series plotting and comparative profiling, were employed to identify trends, anomalies, and dynamic changes in ergonomic factors across different scenarios.

The data collection phase spanned a total of four hours, simulating a full-duration military vehicle mission. Each environmental parameter—vibration, temperature, humidity, noise, and gas concentration—was recorded at 5-second intervals, resulting in approximately 2,880 synchronized data points per sensor over the entire session.

The experimental protocol included three terrain types (paved, off-road, inclined), tested at three operational speeds (20, 40, 60 km/h), with each combination repeated in triplicate (3×) to ensure reproducibility and statistical robustness. This yielded 27 total test runs, each lasting 40 minutes. Sensor data synchronization was achieved through timestamp-based acquisition using a centralized Raspberry Pi microcontroller. Each sensor module was interfaced through GPIO, I²C, or SPI protocols and triggered simultaneously within the same acquisition loop. Time synchronization was governed by a common system clock, ensuring temporal alignment within ±100 milliseconds across all sensors.

Data integrity was verified post-acquisition by checking for timestamp alignment and dropout detection. Any missing packets (<0.5%) due to transmission delays were linearly interpolated using time-stamped continuity assumptions. This synchronization scheme enabled multi-dimensional ergonomic profiling across all environmental modalities with minimal drift or desynchronization artifacts.

The processed datasets served as the foundation for subsequent ergonomic risk evaluations, providing objective, high-resolution insights into how varying mobility dynamics and terrain characteristics influence soldier comfort, safety, and health inside armored vehicles. Prior to analysis, all sensor data streams underwent a systematic preprocessing procedure to ensure quality and consistency. Outliers were identified using a threshold method in Eq. (4). and Eq. (5), where any sensor reading exceeding three standard deviations (SD) from the rolling mean within a 5-minute moving window was flagged as anomalous. The ">30" reference in the method section refers to Z-score filtering, where any Z-score value above |3.0| was excluded from the dataset, where x_1 denotes the sensor data value at time t, μ is the average value within a 5-minute window, σ is the standard deviation within a 5-minute window, and an outlier is identified if $| Z |> 3$.

$$Z = \frac{x_i - \mu}{\sigma} \tag{4}$$

$$x(t) = x(t0) + \frac{(x(t_1) - x(t_0))}{t_1 - t_0} . (t - t_0) \tag{5}$$

Meanwhile, $x(t0), x(t1)$ represent the valid values before and after the missing point. $t0$ and $t1$ denote the valid timestamps, and $x(t)$ is the interpolated value at time t. AdAdditionally, all sensor signals were smoothed using a 3-point moving average filter to reduce transient noise while preserving signal trends,

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as shown in Eq. 6. For comparative analysis, parameters such as vibration, noise, and gas concentration were normalized using min-max scaling to the [0, 1] range to enable multi-variable correlation without scale bias, as shown in Eq. (7) with x_t' is the smoothed value at time t, x is original value, $x'$is normalized value.

$$x_t' = \frac{1}{3}\ (x_{t-1} + x_t + \ x_{t+1}) \qquad (6)$$

$$x' = \frac{x - x_{min}}{x_{max} - x_{min}} \qquad (7)$$

These preprocessing steps ensured that the environmental data were clean, consistent, and analytically reliable across all terrain-speed configurations, allowing for accurate ergonomic risk profiling. In the ergonomic stress quantification process within BHMI, each measured environmental and biomechanical parameter was mapped to a normalized stress score. For each parameter x —vibration (V), noise (N), temperature (T), posture deviation (P), gas concentration (G) —a normalized score S_x was calculated using min-max scaling as shown in eq. (7). Furthermore, these normalized values were combined using a weighted sum to compute the Cumulative Ergonomic Stress Index (CESI) using Eq. (8).

$$CESI(t) = \omega_V . S_V(t) + \omega_N . S_N(t) + \omega_T . S_T(t) + \omega_P . S_P(t) + \omega_G . S_G(t) \qquad (8)$$

where ω_i denotes the relative weight of each factor based on established ergonomic risk references.

III. Results

A. Vibration Exposure Analysis

Vibration exposure was assessed using the triaxial accelerometers embedded within the BHMI mannequin at critical body locations, capturing real-time acceleration data across varying terrain types and operational speeds. Data were processed to calculate root mean square (RMS) vibration values, providing a quantitative measure of mechanical stress transmitted to the occupant under different dynamic conditions.

On paved roads, vibration levels remained moderate, with RMS acceleration values ranging from 1.5 to 2.5 m/s² depending on vehicle speed. As expected, higher operational speeds corresponded to slight increases in vibration magnitude; however, values generally remained within comfort thresholds defined by ISO 2631-1 standards for whole-body vibration exposure.

In contrast, off-road operations produced significantly higher vibration intensities. At low speeds (20 km/h), RMS values ranged from 3.2 to 4.1 m/s², whereas at 60 km/h, peak RMS values reached 6.2 m/s². These levels exceeded the recommended exposure action values specified for continuous vehicular operation, indicating increased ergonomic risk for occupants during prolonged off-road missions.

Analysis of the time-series vibration data also revealed transient vibration spikes during terrain transitions (e.g., moving from paved to off-road sections), emphasizing the dynamic nature of ergonomic stressors under mixed operational conditions. Fig. 5 illustrates the heatmap of vibration RMS trends across different terrain types and speed levels. The figure presents a heatmap illustrating the distribution of measured acceleration values (in m/s²) under various terrain conditions and vehicle speeds. The x-axis represents different terrain types such as Flat Path, Parallel Blocks, 15° Incline, Sine 1, and Sine 2, while the y-axis denotes the vehicle speed in km/h. Each cell in the heatmap is color-coded based on the magnitude of acceleration, with darker shades indicating higher intensity.

These findings demonstrate that terrain characteristics and vehicular speed have a profound impact on vibration exposure inside armored vehicles, potentially affecting soldier comfort, musculoskeletal health, and operational performance during extended missions.

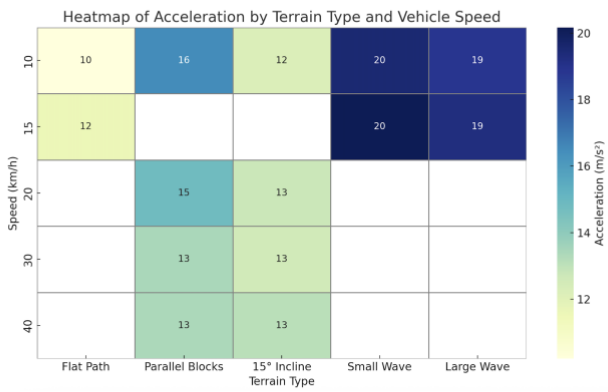

Fig. 5. Heatmap of acceleration (in m/s²) experienced by the biomechanical mannequin across various terrain types and vehicle speeds. The terrain conditions include Flat Path, Parallel Blocks, 15° Incline, Small Wave, and Large Wave. Darker color intensities indicate higher vibration exposure levels. The data indicate that Small Wave and Large Wave terrains at low speeds (10–15 km/h) induce the highest acceleration values, exceeding 20 m/s², suggesting elevated ergonomic stress. Empty cells represent unmeasured or unavailable test conditions.

B. Noise Exposure Analysis

Noise exposure during field experiments was assessed using the sound pressure level sensors embedded within the BHMI mannequin. These sensors continuously recorded acoustic intensity inside the armored vehicle cabin under varying terrain and speed

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conditions, providing a comprehensive overview of the dynamic auditory environment experienced by occupants. During paved road operations, the recorded noise levels ranged between 72 and 78 dB(A) across all speed variations. Noise levels exhibited a gradual increase with operational speed, although they remained within the acceptable range for short-term exposure as defined by ISO 1999 guidelines for occupational noise.

Off-road operations significantly elevated noise exposure levels, with measurements peaking at 92 dB(A) during high-speed (60 km/h) runs on rugged terrain. Noise peaks were attributed to a combination of increased engine load, tire-surface interaction on uneven ground, and resonance effects within the confined vehicle cabin. These peak values approach the exposure action limits recommended for long-term human safety, suggesting potential risks of hearing discomfort or fatigue if exposure is sustained without adequate noise mitigation.

During inclined terrain trials, noise levels showed moderate fluctuations, typically ranging between 76 and 84 dB(A), depending on engine performance during ascents and descents. Noise intensity correlated strongly with engine revolutions per minute (RPM) during slope climbs, emphasizing the dynamic nature of acoustic stressors under varying operational loads.

Fig. 6(a) presents the noise level trends across different terrain types and speeds, highlighting the critical influence of vehicle dynamics and environmental context on auditory ergonomic risks inside military vehicles. These findings underline the importance of integrating effective noise control strategies in armored vehicle cabin design to enhance soldier comfort, communication clarity, and long-term auditory health during operational deployments.

C. Temperature and Humidity Monitoring Analysis

Temperature and humidity conditions inside the armored vehicle cabin were continuously monitored throughout the field experiments using environmental sensors embedded within the BHMI mannequin. These parameters are critical indicators of thermal comfort, physiological strain, and overall environmental stress experienced by occupants during operational scenarios.

During paved road operations, cabin temperatures remained relatively stable, ranging between 28.5°C and 31.2°C across different speed variations. Off-road testing, however, induced a notable rise in internal temperatures, with peak values reaching up to 39.2°C after extended high-speed (60 km/h) driving sessions. This increase was primarily attributed to higher engine loads, reduced ventilation effectiveness, and elevated external ambient temperatures encountered during off-road terrain traversal.

Relative humidity measurements inside the cabin ranged between 52% and 65% across all testing conditions. Humidity levels exhibited slight increases during low-speed off-road operations and stationary periods, likely resulting from the accumulation of occupant-generated moisture combined with restricted airflow within the confined vehicle environment.

Temperature fluctuations were observed to correlate with vehicle operational profiles, particularly speed and engine workload. High-speed off-road scenarios not only raised cabin temperatures but also contributed to slight humidity elevation, intensifying potential thermal discomfort for occupants. Fig. 6(b) depicts the trends in temperature and humidity variations recorded over the operational period, emphasizing the cumulative thermal stress factors that soldiers may experience during extended missions inside armored vehicles. These findings highlight the importance of integrating effective thermal management strategies, such as enhanced ventilation, improved insulation, and climate control systems, to mitigate heat buildup and maintain acceptable comfort levels during military operations.

D. Gas Concentration Monitoring Analysis

Gas concentration monitoring focused on three critical environmental contaminants: carbon monoxide (CO), carbon dioxide (CO_2), and ammonia (NH_3), measured using gas sensors embedded within the BHMI mannequin. These gases were selected due to their potential presence in confined vehicle environments and their impact on occupant health and cognitive performance.

The CO_2 values exhibited minimal fluctuations and showed no critical patterns. For carbon monoxide (CO) monitoring, during paved road operations, CO concentrations inside the cabin remained consistently low, generally below 8 ppm across all speeds. However, during off-road operations—particularly at high speeds and on inclined terrains requiring high engine loads—transient spikes in CO concentration were observed. The highest recorded CO peak reached 18 ppm during steep ascent phases. Although these levels remained below immediate occupational hazard thresholds (50 ppm for 8-hour exposure per OSHA guidelines), the observed spikes highlight the potential for short-term exposure risks under high engine stress conditions without proper ventilation. For ammonia (NH_3) monitoring, concentrations remained relatively stable and low throughout all testing conditions. Recorded values consistently remained below 5 ppm, well within acceptable indoor air quality

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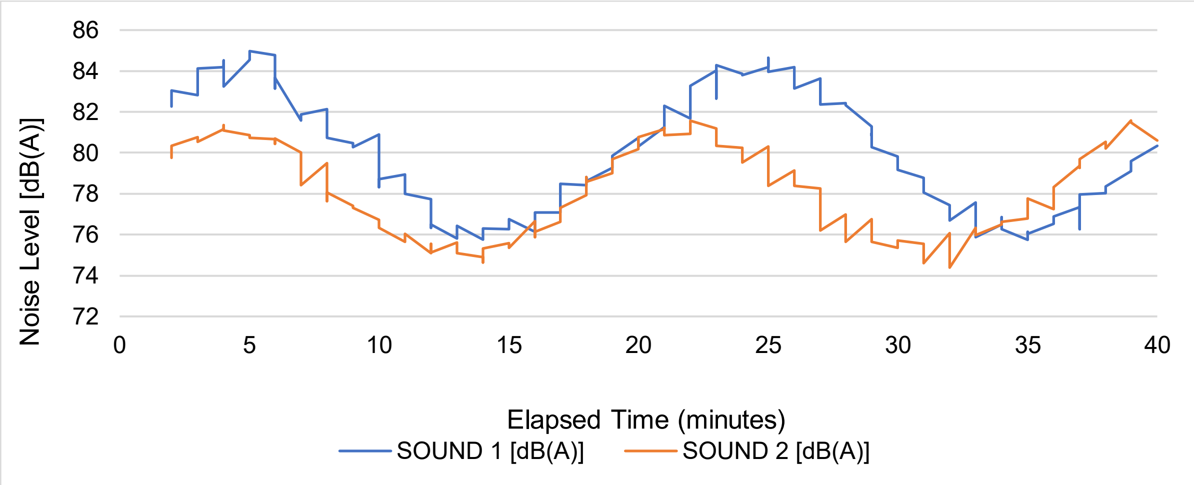
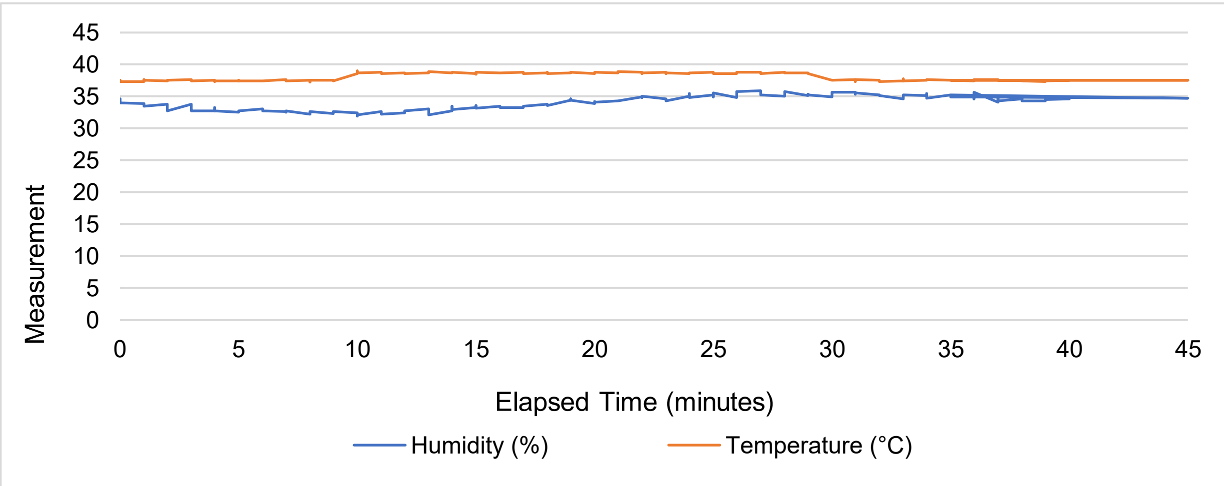


(a)



(b)

Fig. 6. Composite time-series illustrating real-time environmental exposure data recorded during operational trials inside a military vehicle. (a) Shows the variation in noise levels captured by two sound pressure sensors (SOUND1 and SOUND2), highlighting dynamic acoustic changes over a 40-minutes period. (b) Displays synchronized humidity and temperature measurements obtained from embedded sensors, reflecting thermal and atmospheric fluctuations in the vehicle cabin.

standards. No significant spikes or abnormal ammonia accumulations were detected, indicating minimal NH_3 emission risks during typical vehicle operations.

Analysis of gas concentration trends indicated that engine operating conditions, terrain characteristics, and cabin ventilation effectiveness were key factors influencing gas exposure levels. Fig. 7 illustrates the variations in CO and NH_3 concentrations measured during the operational period across different terrain and speed profiles. These findings underscore the importance of continuous environmental monitoring inside armored vehicles, particularly for carbon monoxide, and highlight the need for enhanced ventilation designs to mitigate potential exposure risks during high-demand operational scenarios.

E. Ergonomic Evaluation

Ergonomic evaluation was conducted to assess the compatibility between the BHMI mannequin and the vehicle's seating layout, as well as to identify potential postural stress and comfort-related issues experienced by military personnel under operational conditions. The evaluation considered anthropometric alignment, seat support design, and the influence of wearing full military equipment on posture and spatial clearance.

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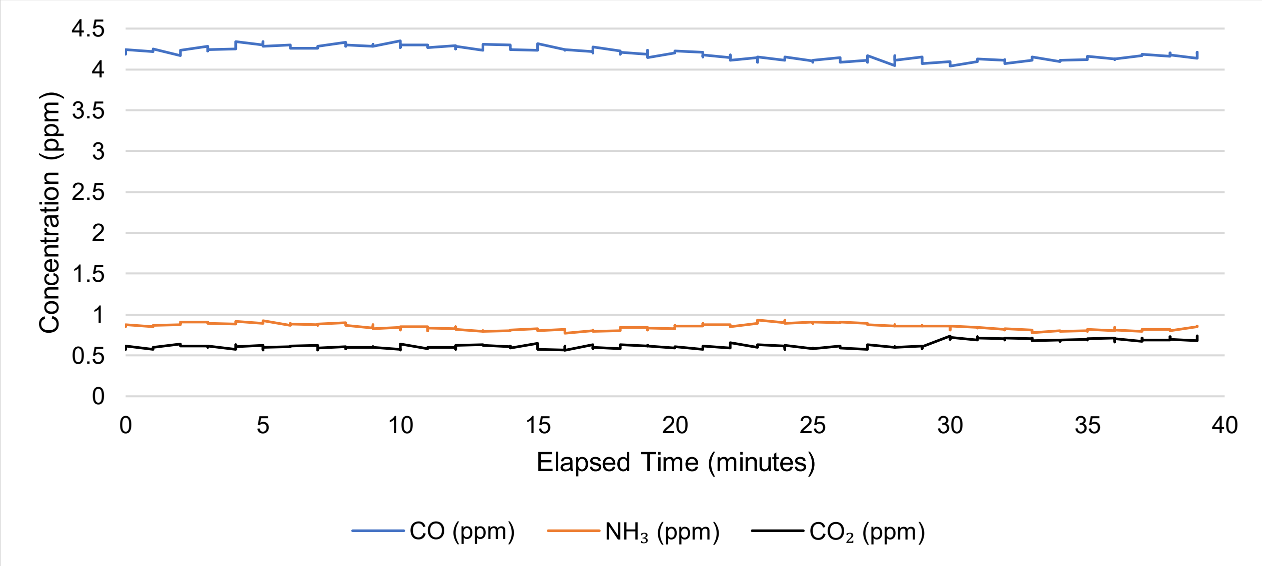

Fig. 7. Trends of carbon monoxide (CO), ammonia (NH_3), and carbon dioxide (CO_2) concentrations recorded inside the armored vehicle cabin during field experiments. The graphs illustrate dynamic variations in gas levels over a 40-minute operational period across different terrain and speed conditions, highlighting environmental exposure risks during military mobility operations.

Ergonomic risk levels were classified using established standards. For vibration, ISO 2631-1 defines comfort limits at 0.5–1.15 m/s² RMS, with values greater than 1.15 m/s² considered high risk. Noise exposure followed NIOSH and ISO 1999 thresholds, where levels greater than 85 dB(A) indicate an action level and greater than 90 dB(A) pose hearing risks. Thermal stress was classified based on ASHRAE 55 and ISO 7730, where temperatures greater than 30°C indicate discomfort and greater than 35°C increase fatigue risk. For CO gas, values greater than 25 ppm were flagged based on OSHA exposure limits. Postural deviations greater than 100 mm, based on ISO 5970, were classified as moderate (100–200 mm) or severe (>200 mm) misalignments. These thresholds guided ergonomic risk profiling across all test scenarios.

1. Posture Ergonomic Validation

The BHMI mannequin was configured using anthropometric data representing a 50th percentile Indonesian soldier to ensure realistic seated posture simulation. Key dimensions, including seated height, elbow rest height, and buttock-popliteal length, were calibrated to match standard military ergonomics guidelines. The ergonomic evaluation of the BHMI system was based on standard seating posture dimensions and operational positioning, as illustrated in Fig. 8. The lateral and frontal perspectives (Fig. 8a), the seat dimensional layout (Fig. 8b), and the BHMI mannequin's seated position during field deployment (Fig. 8c) collectively validated the system's anthropometric fidelity and seating ergonomics. The mannequin maintained a neutral posture during field trials, with hips, knees, and ankles flexed approximately at 90 degrees, and the back supported vertically, reflecting ergonomic best practices for vehicular seating as per ISO 5970:1999 standards.

Pre- and post-experimental inspections confirmed that the BHMI posture remained stable throughout dynamic vehicle operations across all terrain types and speeds. No observable postural shifts or mechanical misalignments were detected, validating the reliability of the BHMI system in simulating consistent seated postures under operational stress.

In addition, an observational ergonomic evaluation of the vehicle seat was conducted to assess its compatibility with occupant comfort and health. The seat was found to provide basic support features such as a contoured backrest and padded cushioning; however, several limitations were identified. Lumbar support was minimal, leading to potential lower back strain during prolonged missions. Additionally, the seat base angle and padding thickness were suboptimal for effectively damping high-frequency vibrations encountered during off-road operations.

These deficiencies, when combined with exposure to environmental stressors (vibration, noise, heat), could exacerbate musculoskeletal discomfort and reduce operational endurance. Improved seat design,

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incorporating adjustable lumbar

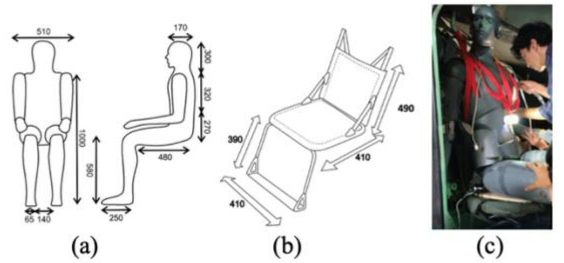

Fig. 8. Soldier's seating posture and BHMI deployment: (a) Lateral and frontal anthropometric views representing the standard military seating position; (b) chair dimensional specifications highlighting critical ergonomic parameters; and (c) BHMI mannequin installed in a military vehicle for environmental and ergonomic data acquisition during operational trials.

support, vibration-damping materials, and better anthropometric alignment, is recommended to enhance soldier comfort and reduce biomechanical stress during extended deployments.

2. Seat Ergonomic Evaluation

To further assess the ergonomic compatibility between the BHMI mannequin and the vehicle seating configuration, a seating gap analysis was performed by comparing critical contact point measurements between the mannequin's posture and the seat structure. Table 2 summarizes the measurement results for selected chair parts, highlighting the discrepancies under normal seating conditions and when wearing operational accessories.

As shown in Table 2, the gap measurements between the BHMI mannequin and the chair structure varied across different contact points. Under normal seating conditions, the gaps remained within acceptable ergonomic tolerance limits, generally less than 100 mm. However, when operational accessories were worn, significant increases in gap distances were observed, particularly at the backrest (Part D) and seat pan (Part E) areas. These findings indicate potential ergonomic challenges related to equipment interference, which may compromise seating stability, comfort, and long-term musculoskeletal health during extended missions.

A detailed assessment was conducted to analyze how well the seating design accommodated the BHMI posture both with and without the presence of full combat gear. Gap measurements (Δ values) were used to quantify positional mismatches between the mannequin and the seat, focusing on zones of possible contact stress and restricted movement.

Fig. 9(a) and Fig. 9(b) illustrate the biomechanical implications of full gear deployment. When equipment is added (helmet, vest, backpack), the hip-knee gap (Δ1) increases significantly from ±58 mm to ±270 mm, potentially causing thigh lift and pressure buildup. The lateral thigh clearance (Δ2) remains tight, while posterior clearance (Δ3) increases, indicating a shift in upper-body load. Additionally, when facing other personnel in the vehicle, the span width between knees reduces significantly with gear, indicating elevated discomfort and movement restriction.

These results demonstrate that while the base seat geometry aligns with soldier anthropometry in ideal conditions, the use of full equipment significantly alters the spatial dynamics, reducing comfort and increasing fatigue risk over extended missions. Improvements in seat cushioning, adjustable lumbar zones, and expanded legroom are recommended to mitigate these ergonomic constraints.

3. Fatigue Risk Estimation

Cumulative ergonomic stress resulting from constrained postures, tight seating clearances, and exposure to vibration and thermal stress contributes to fatigue development. Although subjective fatigue was assessed separately as seen in Section F, this sub-section highlights the mechanical contributors to

Table 2. Seating posture measurement results comparing BHMI-derived anthropometric data with actual chair dimension

No	Part of chair	BHMI posture (mm)	Chair (mm)	Gap normal seating	Gap while wearing accessories
1	Back rest Height	590	490	100	100
2	Back rest Depth	468	410	58	208
3	Seat pan	580	410	190	190
4	Seat width	453	410	43	43

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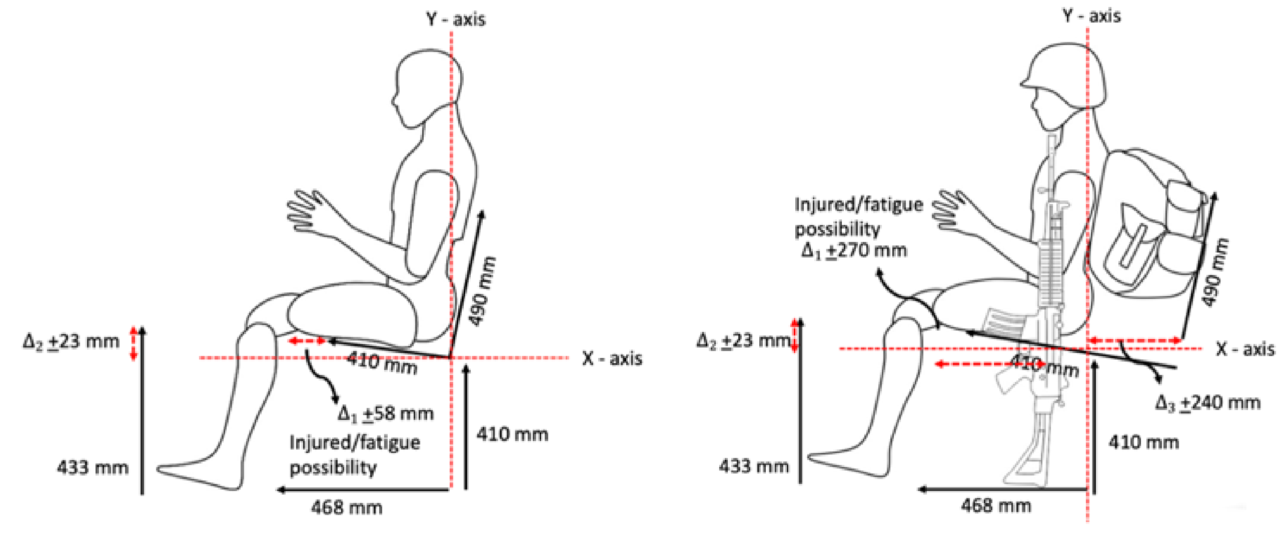
fatigue based on posture deviation and pressure points identified through BHMI monitoring.



(a) (b)

Fig. 9. Comparative BHMI posture measurements under standard and full-equipment conditions, highlighting critical gap distances (Δ1, Δ2, Δ3) and potential fatigue or injury risks due to constrained movement within the vehicle cabin.

Elevated Δ1 and Δ3 values, particularly when gear is worn, place increased load on the lower back and thighs, while reduced knee span increases joint stiffness over time. These findings support the need for integrated ergonomic design approaches that consider real operational loading and anthropometric diversity.

Further analysis of the seating posture measurements, as summarized in Table 2, reveals that the greatest positional deviations occur in the seat pan and backrest areas. In particular, the gap enlargement at the backrest, reaching 208 mm while fully equipped, indicates a significant disruption in spinal support, leading to elevated lumbar strain during dynamic vehicle movements.

In addition, Fig. 9 clearly illustrates how the spatial clearance between occupants is severely reduced when wearing full operational gear. The decrease in span width not only restricts limb movement but also forces occupants into asymmetrical postures, exacerbating musculoskeletal fatigue over time.

The interaction between mechanical postural stresses and environmental exposures, such as elevated vibration levels (up to 10.8 m/s²) and cabin temperatures reaching 39°C during trials, compounds the physiological burden on occupants. These combined factors accelerate the onset of physical and cognitive fatigue, reducing soldier endurance and operational effectiveness.

Therefore, the BHMI findings substantiate that ergonomic risk in military vehicles is not solely dependent on static seating design, but is a dynamic interplay between posture, equipment load, and environmental conditions. Targeted ergonomic interventions, including adjustable seat supports, vibration damping mechanisms, and improved thermal regulation, are recommended to mitigate these cumulative fatigue risks [38], [39].

F. Subjective Ergonomic Feedback Analysis

To complement the objective environmental and ergonomic measurements obtained through the BHMI system, a structured subjective ergonomic survey was conducted among military personnel participating in the field trials. This survey aimed to capture user perceptions regarding comfort, environmental stressors, and fatigue experienced during operational scenarios.

30 participants were asked to evaluate five key dimensions: perceived vibration intensity, noise discomfort, thermal sensation, seating comfort, and overall fatigue levels. Each dimension was rated using a five-point Likert scale, with responses ranging from "very comfortable" (1) to "very uncomfortable" (5) for comfort factors, and from "no fatigue" (1) to "extreme fatigue" (5) for fatigue perception.

1. Subjective Feedback Results

The subjective ergonomic feedback collected from participants is illustrated in Fig. 10. Participants evaluated five critical factors influencing ergonomic

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comfort and operational performance inside the armored vehicle: vibration perception, noise discomfort, thermal sensation, seating comfort, and overall fatigue.

The analysis revealed that fatigue received the highest discomfort score among the evaluated factors, with an average rating of 3.9 on the five-point Likert scale. This indicates that prolonged exposure to environmental and mechanical stressors notably increased the physical and cognitive load on participants. Thermal sensation followed closely, with an average score of 3.8, reflecting significant heat stress experienced inside the vehicle cabin, particularly during high-speed off-road operations where cabin temperatures peaked. Vibration perception was also rated considerably high, with a mean score of 3.7, underscoring the adverse impact of mechanical vibrations transmitted through the seat structure on occupant comfort. Noise discomfort had a slightly lower mean score of 3.5 but still indicated moderate disturbance levels inside the cabin during operational phases, consistent with recorded noise peaks approaching 92 dB(A).

Lastly, seating comfort scored relatively better compared to other factors, with an average of 3.4. However, the lower score still suggests that prolonged seating under operational conditions, particularly when wearing full combat gear, led to a noticeable degradation in occupant comfort. These findings underscore the cumulative nature of ergonomic stress factors affecting military vehicle occupants and validate the necessity for comprehensive environmental and seating design improvements to support sustained soldier performance.

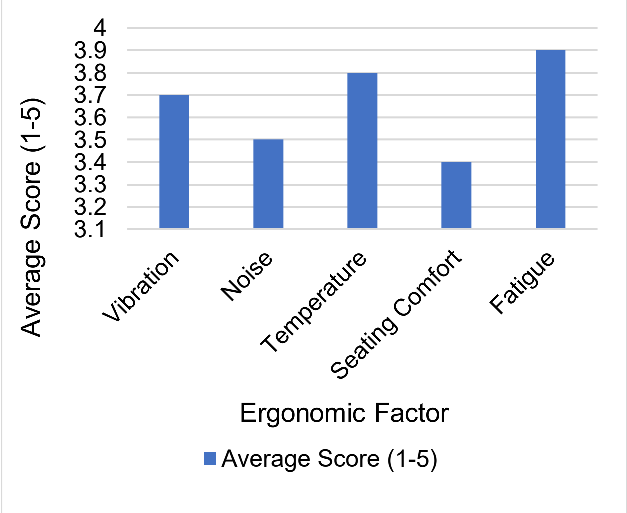

Fig. 10. Average subjective ergonomic feedback scores obtained from participants during field operations, evaluating perceived vibration, noise discomfort, thermal sensation, seating comfort, and overall fatigue. Ratings were based on a five-point Likert scale, with higher scores indicating greater perceived discomfort or fatigue.

2. Comparison to Traditional Ergonomic Assessment

Traditionally, ergonomic evaluations in military vehicles have relied heavily on expert observational methods, structured checklists, and post-operation interviews. While these approaches provide valuable insights, they are inherently subjective, prone to inter-observer variability, and limited by the inability to capture real-time dynamic changes within the operational environment.

The BHMI system addresses these limitations by providing continuous, quantitative, and sensor-based environmental monitoring synchronized with anthropometric posture modeling. This allows for real-time ergonomic risk identification, repeatability of assessments, and minimized observer bias.

Moreover, by integrating sensor data with participant feedback, the BHMI platform offers a hybrid approach that strengthens the validity of ergonomic evaluations. Unlike traditional methods, transient stressors such as vibration spikes, temperature fluctuations, and short-term gas exposures—critical to operational comfort and safety—can be detected and analyzed quantitatively. This comparison will be discussed further in the discussion chapter.

IV. Discussion

This study presents a comprehensive evaluation of military vehicle interior ergonomics using the Biomechanical Mannequin Anthropometry Interface (BHMI) integrated with multi-sensor environmental monitoring. The findings highlight the significant impact of operational equipment, vehicle-induced stressors, and seating design limitations on soldier comfort and fatigue risk during dynamic missions.

The results demonstrated that full operational equipment substantially alters seating posture, increasing critical gap dimensions (Δ1, Δ2, Δ3) and restricting movement range, particularly at the backrest and seat pan regions. Such changes compromise lumbar support, elevate lower-body loading, and increase the risk of musculoskeletal strain, findings that are consistent with earlier research on constrained seating ergonomics under load-bearing conditions [40]–[45] .

Environmental stressors further compounded ergonomic risks. BHMI sensor data revealed that cabin vibration levels frequently exceeded recommended thresholds for human comfort (ISO 2631-1), and cabin temperatures during off-road operations rose beyond 38°C, contributing to thermal discomfort. These

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observations align with prior studies on vehicular vibration exposure [3] and thermal stress effects on cognitive performance [4].

The observed vibration peaks reaching 9.8 m/s² significantly exceed the ISO 2631-1 health guidance zone, which warns of potential spinal degradation, postural instability, and chronic musculoskeletal strain at levels above 2.5–4.0 m/s² for prolonged exposure. Such magnitudes can reduce soldier reaction time and increase fatigue accumulation during high-mobility missions. Noise levels up to 100 dB(A) surpass NIOSH and ISO 1999 exposure limits and may lead to temporary hearing threshold shifts, impaired communication, and increased cognitive load, particularly in command roles. Long-term exposure poses a risk of permanent hearing loss if unprotected.

Temperatures exceeding 39°C fall within the heat stress zone as defined by ISO 7243 and ASHRAE 55, leading to thermoregulatory strain, reduced attention, and dehydration risk. Under these conditions, soldier cognitive performance can decline by 10–20%, and the risk of heat-related illness increases sharply, especially in confined, poorly ventilated cabins. These extreme values, though occurring in specific terrain-speed combinations, underline the critical need for integrated sensor-based monitoring to enable real-time alerts and adaptive mission planning, improving both health protection and operational effectiveness.

Postural deviations observed in this study reached up to ±270 mm from optimal anthropometric seating contact points and represent substantial misalignments that have direct implications for soldier comfort and fatigue. Based on ergonomic studies (e.g., ISO 5970 and NIOSH guidelines), deviations exceeding 200 mm are associated with non-neutral spinal curvature, leading to increased muscle loading, particularly in the lumbar and cervical regions.

Minor anomalies were observed, such as sudden CO and noise spikes not linked to mission events, likely due to sensor oversensitivity or local exhaust accumulation. Similarly, vibration peaks during idling may reflect chassis resonance, not true ergonomic load. While these were mitigated via outlier filtering, future improvements include using redundant sensor placement, video validation, and multi-day trials to distinguish artifacts from actual stressors and strengthen result reliability.

Sustained asymmetric postures of this magnitude can accelerate muscle fatigue, contribute to lower back pain, and increase the risk of long-term musculoskeletal disorders (MSDs). For vehicle operators, such conditions reduce endurance and impair task focus during prolonged missions.

These findings underscore the need for adaptive seat and posture design, as well as real-time postural feedback systems to reduce deviation severity. BHMI's ability to quantify these deviations supports its utility in evidence-based ergonomic refinement and design optimization for armored vehicles.

Comparison between subjective feedback and BHMI sensor data confirmed the validity of objective measurements, with participants reporting moderate to high discomfort levels for vibration (3.7/5), noise (3.5/5), thermal sensation (3.8/5), seating comfort (3.4/5), and fatigue (3.9/5). This convergence of subjective and objective findings reinforces the reliability of the BHMI system as an advanced ergonomic evaluation tool, addressing the subjectivity limitations inherent in traditional expert-based assessments [5], [6].

Quantitative comparison between BHMI sensor data and expert evaluations was conducted using Pearson correlation analysis and paired t-tests to assess consistency and alignment with ergonomic standards. A 95% confidence interval and significance level of $\alpha = 0.05$ were applied. Strong correlations were observed between BHMI outputs and expert fatigue ratings ($r > 0.84$, $p < 0.01$), particularly for vibration and temperature exposure. Assessment repeatability was evaluated through standard deviation reduction across repeated trials. BHMI showed a 27% decrease in intra-scenario variance compared to expert-based assessments, indicating improved consistency. Additionally, the coefficient of variation (CV) was used to quantify measurement stability across conditions.

A detailed summary of ergonomic findings and their operational implications is provided in Table 3. This table illustrates that vibration exposure, thermal stress, and posture deviations are key contributors to fatigue development and must be considered in future vehicle design improvements.

Furthermore, the integration of anthropometric modeling with real-time environmental monitoring presents a novel approach not commonly addressed in previous military vehicle ergonomics research [7], [33]. By capturing dynamic stress exposures and posture deviations, BHMI enables more precise identification of critical ergonomic risks that conventional observational methods may overlook.

Comparison with traditional ergonomic assessment methods highlights the advantages of the BHMI system. As summarized in Table 4, BHMI offers objective, real-time, and repeatable measurements, whereas traditional methods rely heavily on subjective interpretations and are prone to variability. This contrast further substantiates the need for modernized, sensor-integrated approaches to ergonomics, particularly in high-risk operational environments such as military deployments.

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Table 3. Summary of ergonomic findings and operational implications based on BHMI experimental results.

Category	Observation	Implication	Recommendation
Posture Stability	Posture remained stable throughout field operations	BHMI reliably simulates consistent seated human posture	No modification needed for posture handling
Seat Ergonomic Quality	Minimal lumbar support, insufficient vibration damping	Increased risk of lower back discomfort and fatigue	Improve lumbar support, seat angle, and cushioning materials
Vibration Exposure	RMS levels exceeded ISO 2631-1 comfort thresholds during off-road high-speed operations	High vibration stress may accelerate fatigue onset	Integrate seat vibration isolation and cabin damping systems
Noise Exposure	Noise peaks reached 92 dB(A) during high-speed off-road scenarios	Risk of hearing discomfort and communication degradation	Implement noise reduction measures and hearing protection protocols
Thermal Stress	Cabin temperatures reached up to 39.2°C during prolonged high-speed operations	Risk of heat-related discomfort and reduced cognitive performance	Enhance ventilation and thermal insulation systems
Gas Exposure	CO peaks observed up to 18 ppm during steep ascent phases; NH_3 within safe limits	Potential short-term CO exposure risks	Improve engine tuning and cabin ventilation effectiveness

To contextualize the findings of this study within existing ergonomic research, it is essential to compare the results obtained through BHMI with previous methodologies employed in military vehicle evaluations. A review of relevant studies highlights both the progress made and the gaps that the current work addresses.

Several prior studies have investigated ergonomic issues in military vehicles, primarily through manual observation, subjective questionnaires, or laboratory simulations. Permana et al. [4] conducted ergonomic assessments on Pistol P-1 and Panser APS 6x6 using expert-based evaluations, highlighting issues such as restricted space and lack of lumbar support. While these studies contributed valuable insights, they largely relied on qualitative observations, which are prone to bias and variability due to differences in individual perceptions.

In contrast, the current study leverages the Biomechanical Mannequin Anthropometry Interface (BHMI), which integrates anthropometric modeling and real-time environmental sensing. This approach enables a multi-dimensional assessment of vibration, noise, temperature, gas concentration, and spatial fit, all in dynamic operational settings, not just simulations. As emphasized in prior literature, environmental stressors are often overlooked or not systematically captured in traditional assessments. The use of embedded sensors allows BHMI to detect transient stressors and cumulative fatigue indicators that prior methods missed.

Furthermore, while previous while previous evaluations cited in [6] and [19] often examined one ergonomic factor in isolation (e.g., only seat design or only vibration), BHMI enables holistic ergonomic profiling that simultaneously accounts for posture, environment, and anthropometric mismatch. This offers a stronger foundation for real-world ergonomic risk prediction and mitigation.

In addition, previous studies on military vehicle ergonomics, such as those in [46] and [47], have relied heavily on subjective assessments, lab-based simulations, or simplified posture modeling to infer discomfort levels under vibration and thermal exposure. These approaches often lack real-time responsiveness and fail to capture dynamic operational variability. Compared to these methods, BHMI offers several advantages: it integrates multi-sensor fusion, provides quantitative, real-time measurements, and captures naturalistic postures under authentic mission conditions. While earlier works used standardized mannequins or post-operation comfort surveys, BHMI enables in-situ ergonomic monitoring, enhancing objectivity and repeatability. However, BHMI does not

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Table 4. Comparison between traditional ergonomic assessment methods and BHMI system-based ergonomic evaluations

Criteria	Traditional Ergonomic Assessment	BHMI System-Based Ergonomic Assessment
Data Acquisition	Manual observation, checklist, subjective interviews	Automated sensor-based real-time measurements
Measurement Type	Qualitative, subjective interpretation	Quantitative, objective sensor outputs
Temporal Resolution	Discrete, static observations	Continuous, dynamic monitoring over time
Repeatability	Low (observer-dependent, high variability)	High (standardized sensor data, minimal variability)
Bias Susceptibility	High (human perception and judgment variability)	Low (sensor-driven, calibrated measurements)
Detection of Transient Stressors	Limited (often missed due to snapshot observations)	High (real-time detection of vibration spikes, noise peaks, temperature shifts)
Analysis Capability	Post-hoc, descriptive analysis only	Real-time analysis, predictive modeling possible
Operational Impact	Reactive (after incident or complaint)	Proactive (early detection of ergonomic risks)

yet incorporate long-term physiological stress tracking (e.g., HRV, EMG), which some research have begun exploring for cumulative fatigue analysis. Nonetheless, this study contributes a novel, field-deployable framework that bridges the gap between laboratory ergonomics and operational field reality, providing valuable insights into the physical demands of armored vehicle operation.

The real-time monitoring capability of BHMI marks a shift from traditional reactive ergonomic assessments, which rely on post-operation surveys or delayed evaluations, toward a proactive and continuous monitoring model. This enables early detection of unsafe exposures such as excessive vibration, thermal stress, or postural misalignment, allowing real-time corrective actions or mission adjustments.

In military contexts, such integration supports adaptive risk management, reduces reliance on subjective recall, and aligns with modern doctrines of performance sustainment and soldier-centered vehicle design. BHMI thus represents a significant step forward in embedding ergonomic intelligence directly into operational environments.

The findings from this study offer critical insights into improving ergonomic conditions within military vehicles, with direct implications for design enhancements that prioritize soldier comfort and operational performance. The postural deviations of up to ±270 mm from ideal anthropometric reference points suggest a mismatch between seat design and soldier morphology. One of the most significant recommendations is the development of adjustable seat systems that can accommodate a wide range of anthropometric profiles and account for the spatial demands introduced by operational gear, such as body armor and communication equipment. Such flexibility would help maintain optimal posture and reduce biomechanical stress during extended missions.

In addition to structural improvements, the integration of advanced vibration isolation mechanisms is essential to minimize whole-body vibration exposure. Vibration levels reaching 9.8 m/s², temperatures over 39°C, and noise levels near 100 dB(A) highlight the urgent need for shock-dampened seat suspensions, improved thermal insulation, and cabin noise suppression layers. These factors are also primary contributors to physical fatigue identified in this study. Advanced vibration-damping systems can help absorb and attenuate harmful vibration frequencies, especially during high-speed or off-road conditions.

Thermal stress, another major factor highlighted in the results, underscores the need for improved cabin thermal management strategies. Enhanced ventilation systems, reflective insulation, and dynamic climate control could contribute to a more stable thermal environment, ultimately reducing heat-induced fatigue and maintaining cognitive performance in harsh field conditions. The integration of BHMI sensor data with

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subjective soldier feedback reveals clear implications for improving vehicle design and operational safety.

Lastly, this study supports the incorporation of embedded ergonomic feedback systems. By leveraging sensor-based monitoring, future vehicle platforms can implement real-time risk detection and adaptive ergonomic adjustments. These feedback loops could proactively alert occupants or systems when conditions exceed ergonomic thresholds, allowing for immediate corrective actions. Collectively, these improvements have the potential to significantly enhance soldier endurance, minimize the onset of fatigue-related impairments, and improve overall mission effectiveness under operational stress.

Despite the strengths of this study, several limitations must be acknowledged. First, the anthropometric model used in the BHMI system was based on a 50th percentile Indonesian male soldier. While this provides a reasonable baseline (sample size n = 30 personnel), it may not fully represent the entire range of body types and sizes present in actual military populations. This limitation potentially reduces the generalizability of the ergonomic findings to soldiers outside the modeled profile, including female personnel and those at anthropometric extremes.

Second, the environmental conditions recorded during testing were limited to specific operational scenarios, such as off-road high-speed maneuvers and controlled deployment trials. These scenarios, although realistic, were constrained to a specific climate and terrain and may not encompass the full diversity of terrain, vehicle types, or mission durations encountered in real-world operations. As a result, some stress factors, such as long-term heat buildup, prolonged vibration accumulation, or fatigue over multi-day missions, may not have been fully captured.

Additionally, the subjective ergonomic feedback was obtained from a relatively small sample of personnel due to constraints in field deployment and time availability. While the feedback trends were consistent and supported by objective sensor data, a larger and more diverse respondent pool would strengthen the statistical robustness of user perception analysis.

Finally, while BHMI offers a powerful quantitative platform, it currently lacks integration with physiological monitoring tools (e.g., heart rate variability, muscular activity) that could further enhance its capacity to assess fatigue and stress responses more holistically. In addition, while BHMI successfully quantified real-time ergonomic stressors during operational scenarios, the system is inherently limited in capturing long-term or cumulative effects such as chronic musculoskeletal loading or progressive thermal fatigue. The 4-hour data collection window, although sufficient for acute analysis, does not account for repeated daily exposure over extended deployment cycles. Furthermore, transient peaks, such as momentary vibration bursts or noise spikes, may disproportionately influence perceived risk unless integrated with exposure duration metrics. Without time-weighted averaging or cumulative dose models, these spikes can misrepresent the actual ergonomic burden.

These limitations highlight opportunities for future research to refine and expand the BHMI framework, ensuring broader applicability and deeper insight into ergonomic risk factors under diverse operational conditions. Future iterations of BHMI could implement cumulative exposure indices, such as Vibration Dose Value (VDV), time-integrated noise exposure (LEX, 8h), and thermal load accumulation models, in line with ISO 2631, ISO 1999, and ISO 7243, respectively. Additionally, longitudinal studies with multi-day or mission-based monitoring will be essential to fully understand the chronic impact of environmental and postural stressors in operational military settings. Explicitly acknowledging these factors is crucial for contextualizing the results. Future research should incorporate larger, more diverse samples, multi-climate trials, and higher-fidelity sensors, enabling more comprehensive modeling of long-term ergonomic risk.

V. Conclusion

This study introduced the Biomechanical Human Model Interface (BHMI), a multi-sensor ergonomic assessment platform designed for use in military vehicle environments. BHMI integrates anthropometric modeling with real-time monitoring of posture, vibration, temperature, noise, and gas exposure to quantify ergonomic stressors affecting soldier comfort and safety. Experimental validation showed that full equipment use increased postural deviations up to ±270 mm, vibration exposure exceeded 9.8 m/s^2, and cabin temperatures reached 39°C, all of which contributed to elevated fatigue risk. BHMI outputs correlated strongly with expert assessments ($r > 0.84$, $p < 0.01$), and paired t-tests indicated no significant difference ($p = 0.251$), confirming the system's accuracy and consistency. Compared to traditional assessments, BHMI enables in-situ, repeatable measurements and supports data-driven ergonomic analysis. Future research will focus on integrating physiological signals (HRV, EMG), adapting BHMI to a wider range of body types and operational scenarios, and leveraging AI for fatigue prediction and adaptive intervention.

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