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ErgoFit: Real-Time Ergonomic Monitoring and Feedback System Using Inertial Sensors for Musculoskeletal Disorder Prevention

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ABSTRACT : The Work-related muscoloskeletal disorders remain a major challange in industrial environtments due to repetitive movements, unsafe posture, and limited real-time monitoring solutions. Traditional ergonomic assesement methods are often subjective and conducted intermittently, reducing their effectiveness in preventing injuries. This study presents ERGOFIT, an IoT-based ergonomic monitoring system designed to provide continuous and objective posture evaluation using wearable IMU sensors and an Edge Computing architecture. Ten sensor modules were developed and integrated into a wireless network that captures body-segment motion data and processes it locally to minimize latency. A biomechanical model and RULA scoring algorithm were implemented to generate real-time risk assessments, supported by a multimodal feedback interface consisting of visual alerts, audio cues, and a web-based dashboard. System testing demonstrated that the architecture enables fast and reliable data transmission, while the motion visualization interface improves user understanding of posture quality. The findings highlight the potential of ERGOFIT to enhance workplace safety, support operator training, and reduce ergonomic risks through proactive monitoring and immediate feedback.

Keywords – Ergonomics, IMU, Musculoskeletal Disorder, RULA Evaluation, Real-Time Monitoring

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1. INTRODUCTION

Work-related Musculoskeletal Disorders (MSDs) represent a critical challenge in industrial sectors, imposing severe consequences on worker health and organizational productivity. These disorders are not merely physical ailments but substantial economic burdens. In the United States alone, MSDs are the leading cause of occupational illness, costing the sector between $45 and $54 billion annually due to medical expenses and absenteeism [1]. The prevalence is alarmingly high; studies in office-based environments indicate that up to 80% of employees may suffer from MSD episodes within a single year, with over 40% experiencing disabling conditions specifically affecting the neck and lower back [2]. Given these statistics, traditional ergonomic assessment methods—which are often subjective and intermittent—are no longer sufficient to mitigate such widespread risks [3].

In response to this urgency, the integration of Industry 4.0 technologies has ushered in a new era of occupational safety, emphasizing the potential of wearable sensor systems and the Internet of Things (IoT) [4]. By utilizing Inertial Measurement Units (IMUs), it is possible to quantify worker movements in real-time, providing objective data that surpasses the accuracy of conventional observational tools. These IoT-based systems allow for continuous monitoring, theoretically enabling a shift from reactive measures to proactive safety management.

However, the effectiveness of these systems is frequently compromised by their architectural reliance on centralized cloud computing [2]. Although cloud platforms offer powerful analytics, they introduce inherent latency and depend heavily on stable internet connectivity. In high-risk industrial scenarios, a delay of even a few seconds in data transmission can render a posture warning ineffective, as the hazardous event may have already occurred. Moreover, the massive volume of data generated by continuous 24/7 monitoring requires efficient management to extract actionable insights without overwhelming network bandwidth [1].

To bridge this gap, this paper proposes ERGOFIT, an intelligent ergonomic monitoring system designed with an Edge Computing architecture. Unlike traditional cloud-centric approaches, ERGOFIT processes sensor data locally at the network edge, closer to the user. This approach directly addresses latency and connectivity issues while leveraging advanced sensing capabilities [4, 2]. By integrating AI-powered analytics directly into the local infrastructure, ERGOFIT provides instant, real-time feedback to workers, effectively preventing MSD risks before they develop into injuries.

The primary contribution of this study is the design and simulation of a low-latency network infrastructure tailored for ergonomic safety. We demonstrate how shifting the computational load from the cloud to the edge enhances system responsiveness and reliability, offering a robust solution for modern industrial environments.

2. LITERATUR REVIEW

2.1 Musculoskeletal Disorders (MSDs) in the Workplace

Musculoskeletal Disorders (MSDs) are a major occupational health concern across various sectors, contributing to reduced productivity, increased medical costs, and long-term absenteeism. A systematic review found that up to 80% of computer users experience MSDs annually, with over 40% reporting disabling conditions in the neck and lower back [1]. In office settings, prolonged sitting and repetitive upper-limb movements are common contributors to MSDs [2]. In healthcare environments, repetitive tasks, awkward postures, and prolonged standing or sitting significantly increase MSD risk among health workers [5]. These findings highlight the urgent need for early detection and intervention strategies in both office and clinical environments.

2.2 Conventional Ergonomic Evaluation Method

Observation-based ergonomic evaluation methods such as RULA, REBA, and OWAS are widely used to assess working postures. However, these methods are inherently subjective, rely on snapshot observations, and are unable to capture dynamic movement in real time. Conventional assessments often fail to detect early signs of MSDs, especially in high-risk environments like hospitals [5]. Similarly, checklist-based evaluations in office settings frequently lead to inconsistent interpretations and lack adaptability for continuous monitoring [3]. These limitations have prompted researchers to explore sensor-based and automated ergonomic systems.

2.3 Wearable Sensors and IMUs for Posture Monitoring

The advancement of inertial sensors such as accelerometers and gyroscopes enables continuous monitoring of body movement. IMU-based systems can accurately capture changes in body orientation without requiring cameras or controlled lighting. Computer-vision-based ergonomic assessment tools have demonstrated superior accuracy and stability in complex manufacturing environments [4]. These systems are particularly effective in identifying joint angles, repetitive movement patterns, and hazardous postures, making them suitable for both industrial and healthcare applications.

2.4 Edge Computing in Real-Time Ergonomic Systems

Modern ergonomic monitoring systems often rely on cloud computing to process sensor data. While cloud platforms offer powerful analytics, they also introduce latency and dependence on network stability, which can hinder real-time feedback. Edge computing — which processes data locally on devices — significantly improves system responsiveness and reliability [6]. In dynamic work environments, such as manufacturing or clinical settings, edge-based architectures are essential for delivering immediate posture warnings and ergonomic feedback.

2.5 Integration of IMU, Biomechanical Modeling, and RULA

Recent studies have integrated IMU data with biomechanical models to estimate joint orientation using sensor fusion algorithms such as the Extended Kalman Filter (EKF). These models enable three-dimensional motion analysis and the transformation of sensor orientation into anatomically meaningful joint angles. Combining IMUs with automated RULA scoring provides objective and consistent evaluations of upper-limb, neck, and trunk postures [6]. This integration supports both real-time monitoring and retrospective ergonomic analysis.

2.6 Real-Time Ergonomic Feedback

Real-time ergonomic feedback using visual and audio cues enables workers to correct their posture immediately. Wearable feedback systems can reduce the duration and frequency of high-risk postures by increasing workers' awareness during tasks [6]. In ERGOFIT, feedback is delivered through a web-based interface and audio alerts designed to minimize disruption. When combined with edge computing, this system ensures rapid response times, which are critical for posture correction in dynamic work environments.

3. RESEARCH METHOD

This study adopted an applied research design supported by the Agile development methodology to produce the ERGOFIT real time ergonomic monitoring system. The Agile approach was chosen for its iterative and adaptive characteristic, enabling rapid refinement of system components across short development cycles. The research began with a requirement analysis phase involving an extensive literature review and field observations in Indonesia manufacturing settings to identify dominant musculoskeletal risk and operational constraints. These insights informed the initial system specifications, which were continuously updated throughout Agile sprints. System architecture and hardware development followed, including the construction of a 10-unit IMU sensor network, custom PCB fabrication, ergonomic mounting design, and wireless communication integration. Calibration procedures were performed using an optical motion capture system, and iterative improvements were conducted after each test cycle to enhance accuracy and system stability.

The next stage involved algorithmic and interface development. A twenty degree of freedom upper body biomechanical model was built, supported by an Extended Kalman Filter for sensor fusion, while the RULA algorithm was implemented to compute real time ergonomic risk scores. A multimodal feedback system consisting of visual alerts, auditory warnings, and a mobile/desktop application was developed and refined through user centered testing within each Agile iteration. Quantitative data (joint angles, RULA scores, and posture durations) were analyzed descriptively and statistically to assess improvements in posture safety, while qualitative data from structured questionnaires captured user acceptance and perceived effectiveness.

4. RESULT AND DISCUSSION

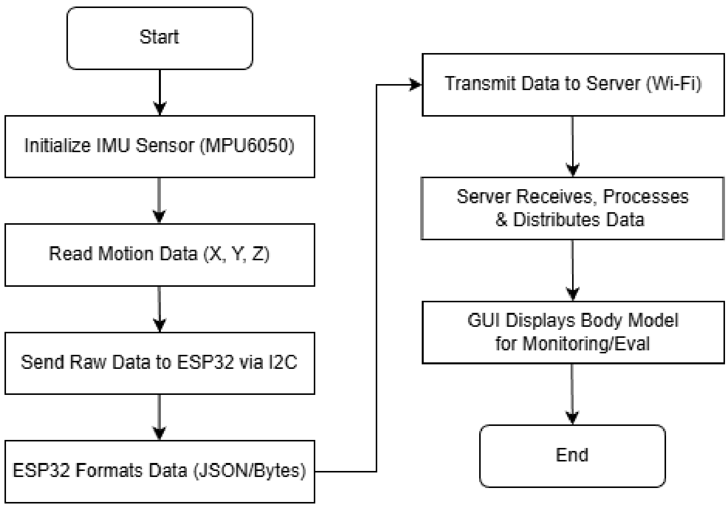

Figure 1. Ergofit System Workflow Diagram

The system begins by activating all hardware components and preparing the data communication workflow. After that, the MPU6050-IMU sensor initialized to ensure accurate motion detection using an appropriate sensitivity configuration and sampling rate. Then, the sensor measures acceleration and rotational movement across the X,Y,Z axes producing raw motion data that represents changes in body orientation. This raw data is transferred to the ESP32 microcontroller through the I2C protocol, allowing the ESP32 to receive direct motion from the sensor. Once received, the ESP32 converts the raw values into a structured data format such as JSON or a byte array to make the information easier for the server to interpret. The formatted data is transmitted to the server over a Wi-Fi connection, enabling real-time motion monitoring without the use of physical cables. The server processes the incoming data to improve information quality including noise filtering and motion estimation and then distributes the processed data to the graphical user interface. The GUI visualizes the motion by displaying a body model, allowing users to observe movement patterns and evaluate motion performance visually. When the sequence is completed, the system can stop or continue the cycle by reading and transmitting data again if continuous monitoring is required.

Figure 2. Hardware Ergofit System

Each module attached to the body is equipped with an IMU sensor (MPU6050), which measures the orientation and motion of the corresponding body segment. The sensor produces acceleration and angular velocity data across three axes, allowing accurate identification of positional changes such as elevation, lowering, rotation, and inclination. The raw data is transmitted to an ESP32 module for initial processing and formatting before being sent to the server via a Wi-Fi connection. On the software side, the system is supported by a website-based platform that incorporates a biomechanical modeling engine, a RULA assessment algorithm, a data visualization interface, and a configuration tool that enables parameter customization based on specific work requirements. This integration ensures that body-movement data can be visualized in real time as a simplified body model that dynamically updates according to sensor orientation.

Beyond enhancing the precision of motion monitoring and evaluation, this technology offers substantial benefits for industrial workers. Accurate motion data enables organizations to identify ergonomic risks, including suboptimal working postures and movement patterns that may lead to musculoskeletal injuries. Through the integrated RULA algorithm embedded in the website, posture-related risk assessments can be performed automatically, rapidly, and consistently. The insights generated can be used to improve workplace design, strengthen operator training, and reduce the likelihood of fatigue or injury resulting from repetitive tasks. Consequently, this system contributes to improved workplace safety, operational efficiency, and overall productivity within industrial environments.

5. CONCLUSION

The development of ERGOFIT demonstrates the potential of integrating wearable IMU sensors with an Edge Computing architecture to improve the accuracy and responsiveness of ergonomic risk monitoring in industrial environtments. By processing data locally, the system reduces latency and enhances reliability, allowing workers and supervisors to receive real-time posture feedback that can help prevent musculoskeletal disorders before they occur. The multimodal feedback system, combined with biomechanical modeling and automated RULA assessment, offers a comprehensive and objective alternative to traditional observational ergonomic methods. Despite these advantages, the system still faces several limitations. The accuracy of IMU-based posture estimation can be affected by sensor drift, misalignment, and variations in mounting placement. Network performance may also fluctuate depending on environmental interference or Wi-Fi congestion, which could influence the consistency of data transmission. Additionally, the current implementation focuses primarily on upper-body monitoring, leaving opportunities for expansion into full-body assessment and broader occupational scenarios. The results indicate that ERGOFIT has strong potential for application in manufacturing, logistics, office ergonomics, and operator training programs. Future extensions may include integrating machine learning for automated posture classification, expanding hardware scalability for large workforce deployments, and incorporating predictive analytics to support long-term ergonomic risk management. Overall, this work contributes meaningful progress toward intelligent, proactive, and accessible ergonomic safety systems aligned with Industry 4.0 initiatives.

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