Portable EMG System for IoT Using MQTT

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Abstract— Conventional electromyography (EMG) systems in clinical settings present limitations including high examination costs (500,000-1,500,000 IDR), bulky equipment, and lack of remote monitoring capabilities. This study develops and validates a portable Internet of Things (IoT)-based EMG system utilizing Message Queuing Telemetry Transport (MQTT) protocol for wireless muscle activity monitoring. The system integrates an EMG V3 sensor module with NodeMCU ESP8266 microcontroller, powered by dual 18650 batteries. Implementation utilized Arduino IDE and IoT MQTT Panel application. Validation comprised functional suitability testing (ISO/IEC 25010:2012), signal characteristics analysis across five subjects with 10 trials each, and repeatability precision evaluation (ISO 17025:2017). The system demonstrated 100% functional suitability. EMG signal characteristics showed average peak-to-peak voltage of 8.95±0.62 mV during relaxation and 10.48±0.58 mV during contraction, with Root Mean Square (RMS) voltage of 1.38±0.11 mV and 1.94±0.21 mV, respectively. Signal frequency-maintained consistency at approximately 50 Hz. Overall repeatability precision achieved 97.62%. This portable EMG system addresses conventional system limitations through wireless connectivity and reduced cost while maintaining measurement accuracy suitable for muscle health monitoring applications.

Keywords— electromyography; EMG V3 sensor module; internet of things (IoT); Message Queuing Telemetry Transport (MQTT); NodeMCU ESP8266

I. Introduction

Human movement relies on coordinated muscle tissue activity controlled by the nervous system, which transmits command signals from the brain through the spinal cord to the muscles [1]. During daily activities, individuals utilize multiple muscle groups, yet they often overlook muscle saturation levels and physiological states, potentially leading to muscle fatigue (caused by repetitive daily activities, exercise, or poor posture) and performance degradation [2]. This becomes particularly problematic in occupational settings where repetitive tasks impose sustained loads on specific muscle groups, contributing to work-related musculoskeletal disorders [3]. In clinical practice, electromyography (EMG) serves as a fundamental technique for evaluating electrical activity produced by skeletal muscles during contraction and relaxation phases [4]. EMG is used to detect changes in muscle electrical activity before clinical symptoms appear because many people work with repetitive muscle loads without realizing the potential for early fatigue.

Current EMG systems in healthcare facilities present significant limitations including bulky equipment, cable dependencies, and high costs ranging from 500,000 to 1,500,000 Indonesian Rupiah per examination, restricting public access to muscle health diagnostics [5]. These conventional systems lack portability and real-time remote monitoring capabilities, necessitating physical presence at medical facilities for assessment [6].

The advancement of Internet of Things (IoT) technology has revolutionized biomedical instrumentation by enabling wireless data transmission, remote monitoring, and cost-effective healthcare solutions [7], [8]. IoT-based medical devices facilitate continuous health monitoring while reducing healthcare costs and improving accessibility [9], [10]. Among various IoT communication protocols, Message Queuing Telemetry Transport (MQTT) demonstrates superior performance in handling multiple concurrent client connections with minimal bandwidth requirements and efficient data transmission [11]. MQTT is adopted for IoT applications because of its simple implementation model [12], [13], performs well when transmitting short messages [13], and used lower power consumption [14].

Several researchers have explored portable EMG systems with varying approaches. Lukar and Setiawan [1] developed an Arduino-based EMG signal detection system for Android platforms, while Bawa and Banitsas [4] conducted comparative studies between low-cost EMG sensors and commercial systems for measuring muscle activity. Hanapi et al. [15] implemented IoT-based EMG monitoring using ESP32 microcontrollers, demonstrating wireless transmission feasibility. However, these systems either lacked comprehensive IoT integration, exhibited high transmission latency, or had limited validation protocols.

Research on EMG signal processing has advanced considerably. Setioningsih [5] investigated the impact of digital and analog filters on surface EMG signals, while Del Olmo and Domingo [16] characterized EMG signals in production environments. Strzecha et al. [17] addressed challenges in processing EMG signals with powerline and cardiac interference. These studies have improved signal quality but often focused on isolated aspects rather than complete system integration.

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Recent studies in IoT-based biomedical systems have demonstrated potential for wireless health monitoring [18],[19]. Various researchers have explored MQTT protocol implementation for medical device communication [20]. Zhang and Navimipour [18] reviewed IoT-based medical management systems, while comprehensive analyses of healthcare IoT devices have been conducted [9].

Despite these technological advances, current portable EMG systems present several limitations: (1) Existing wireless EMG devices often exhibit transmission latency unsuitable for real-time applications; (2) Most published systems lack comprehensive validation following standardized protocols for both functional suitability and measurement repeatability; (3) Limited research provides detailed MQTT performance characterization specific to biomedical telemetry requirements; (4) Few implementations demonstrate integration of all essential components portability, wireless connectivity, and validated accuracy in a single system.

This research addresses these identified limitations by developing a portable EMG system that integrates IoT technology with MQTT protocol for real-time wireless data transmission. The system aims to provide accessible, cost-effective muscle health monitoring while maintaining clinical accuracy standards. The primary objectives include: (1) designing a portable EMG system with wireless connectivity, (2) implementing MQTT protocol for efficient data transmission, (3) validating system performance through functional and precision testing, and (4) evaluating EMG signal characteristics across multiple test subjects.

The novelty of this work lies in the comprehensive integration of EMG V3 sensor modules with NodeMCU ESP8266 microcontrollers and MQTT protocol implementation, creating a complete IoT-based muscle monitoring system. This approach enables real-time data acquisition, wireless transmission, and remote monitoring capabilities while maintaining compact form factor (12.5×9.5×5.4 cm, 400g) and extended battery operation. The system is validated through standardized testing protocols, providing quantified performance metrics across functional suitability, signal characteristics, and measurement repeatability.

II. Method

A. System Design

The system architecture comprises hardware and software components integrated through IoT protocols. Figure 1 illustrates EMG Portable System Circuit Design. The portable EMG system incorporates several key components working synergistically to achieve optimal performance.

1) Signal Acquisition and Conditioning

The EMG V3 Sensor Module (Advancer Technologies) serves as the primary signal conditioning unit, providing essential filtering capabilities through cascaded filter stages: High Pass Filter above 20 Hz, Low Pass Filter below 500 Hz, and the combined Band Pass Filter. This frequency range (20-500 Hz) encompasses the physiological EMG signal spectrum. The module incorporates operational amplifiers for signal amplification and voltage divider circuits for signal scaling to match the ESP8266 Analog-to-Digital Converter (ADC) input range.

Surface EMG signals were acquired using three disposable Ag/AgCl electrodes positioned on the biceps brachii muscle following standard placement guidelines. The active electrode was positioned at the muscle belly, the reference electrode placed distally along the muscle fiber direction, and the ground electrode attached to a bony prominence. Inter-electrode distance was maintained at approximately 20 mm to optimize signal capture. Skin preparation involved cleaning with isopropyl alcohol to reduce skin-electrode impedance.

2) Microcontroller and Processing

The NodeMCU ESP8266 functions as the central processing unit, handling EMG signal processing tasks and implementing MQTT client functionality for wireless data transmission to remote monitoring systems. The device samples EMG signals through its integrated 10-bit ADC and processes the data for transmission via WiFi connectivity.

3) MQTT Communication Architecture

The system implements a publish-subscribe MQTT architecture consisting of three layers: (1) Publisher Layer: NodeMCU ESP8266 devices function as MQTT publishers, acquiring EMG signals and publishing processed data to the broker; (2) Broker Layer: MQTT broker manages the publish-subscribe messaging and maintains client connections; (3) Subscriber Layer: IoT MQTT Panel mobile application subscribes to designated topics and receives real-time EMG data streams for visualization.

Data transmission follows MQTT protocol standards with Quality of Service (QoS) level 1 configuration, ensuring message delivery confirmation. The topic hierarchy enables organized data management and supports multiple device connections.

4) Power Management

Power management represents a critical aspect of the portable design, utilizing dual 18650 batteries with 2500 mAh capacity each, integrated with a TP4056 charging module and Battery Management System (BMS) for extended operational life and safe charging cycles. The system incorporates a ±12V CT (charge-transfer) module that provides stable power supply to the EMG sensor, ensuring enhanced sensitivity and measurement stability across varying operational conditions.

B. System Validation Methodology

1) Functional Suitability Testing

Functional suitability assessment evaluated system performance across four critical parameters following ISO/IEC 25010:2012 standards [21]

- Physical and digital button functionality.
- ESP8266 WiFi module internet connectivity.
- MQTT broker communication establishment.
- MQTT protocol data transmission efficiency.

Each parameter was tested multiple times to determine the success percentage-based system functionality requirements.

2) EMG Signal Characteristics Analysis

Signal characteristics testing employed five subjects performing standardized muscle relaxation and contraction protocols. Testing involved healthy male adult aged 20–30 years volunteers recruited from the university physics department. Each measurement cycle consisted of 5-second relaxation followed by 5-second contraction, repeated 10 times per subject.

Oscilloscope measurements (Figure 2) evaluated:

- Peak-to-peak voltage amplitude (Vp-p)
- Root-mean-square (RMS) voltage
- Signal frequency components

The RMS voltage was calculated by equation (1), where V_i is instantaneous voltage samples and n is the sample count.

$$V_{RMS} = \sqrt{\frac{\sum V_i^2}{n}} \quad (1)$$

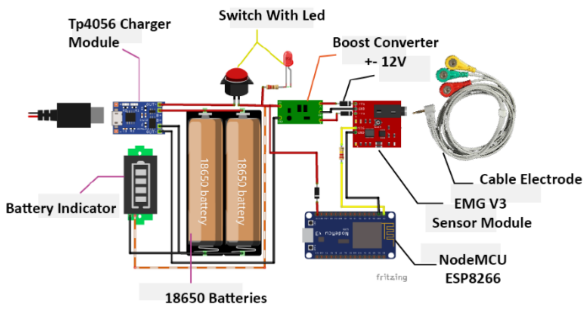


Figure 1. EMG portable system circuit design

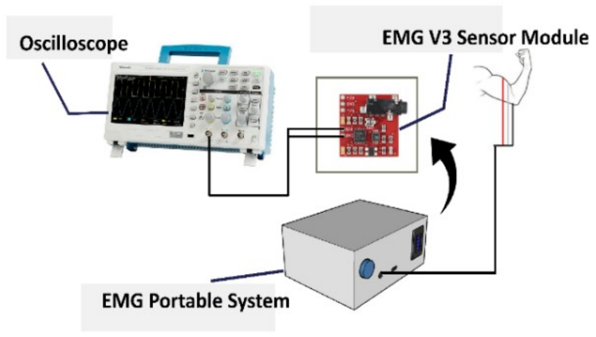


Figure 2. Testing characteristics signal EMG scheme

3) Repeatability Precision Testing

Repeatability precision evaluation assessed measurement consistency under unchanged conditions, following ISO 17025:2017 standards [22]. Each subject performed 10 identical measurement trials with the system to evaluate consistency. The precision percentage was calculated using (2) and (3).

$$Precision\ (\%) = \left[1 - \left(\frac{SD}{Mean}\right)\right] x100\% \quad (2)$$

$$SD = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}} \quad (3)$$

where:

SD : Standard deviation of repeated measurements
Mean ($\bar{x}$) : Arithmetic average measurements
x_i : Individual measurement value
n : Number of repetitions

Overall system precision was determined by averaging individual parameter precisions across all measurements.

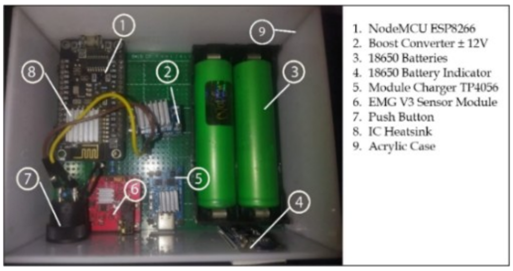
4) Statistical Analysis

Data analysis employed linear regression for signal characterization and statistical correlation assessment. Measurement precision calculations utilize coefficient of variation and standard deviation analysis. All measurements were performed in controlled environmental conditions to minimize external interference.

III. Results and Discussion

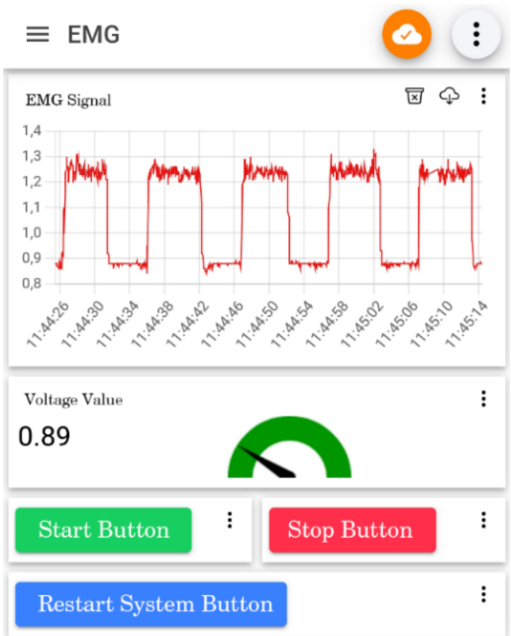
A. System Design Results

A portable electromyography (EMG) system hardware based on the Internet of Things (IoT) with message queuing telemetry transport protocol has been successfully fabricated. The electronic circuit design successfully integrated all components according to the specified pin configuration. The overall system design (Figure 3) resulted in a compact device with dimensions of 12.5 cm × 9.5 cm × 5.4 cm, housed in a white acrylic casing (3 mm thickness) with a total weight of 400 grams. The design prioritizes portability while ensuring component protection and user accessibility. Figure 3(a) shows the assembled hardware system, demonstrating successful integration of all electronic components within the protective casing. The power management system provides stable operation with extended battery life through the implemented BMS functionality. The Arduino IDE-based firmware successfully implements all required functionalities, including EMG signal acquisition, MQTT communication, and IoT integration. Figure 3 (b) illustrates the complete system enclosure with electrode cable connections, control interfaces, and charging port. Figure 3(c) shows the IoT MQTT Panel application interface displaying real-time EMG data transmission. The interface presents live voltage measurements, system status indicators including WiFi connection strength and MQTT broker status, and battery level monitoring. The application enables visualization of EMG signals and system parameters for remote monitoring purposes.



(a)

(b)



(c)

Figure 3. A portable electromyography (EMG) system in (a) Hardware (b) Box, and (c) Software

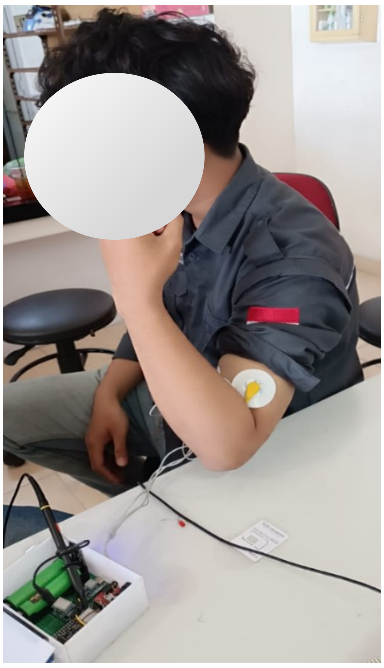
B. System Validation Results

Testing subjects performed standardized muscle relaxation (Figure 4 (a)) and contraction (Figure 4(b)) protocols as described in the methodology section.

1) Functional Suitability Performance

Table I presents the functional suitability testing results, demonstrating 100% success rates across all critical system parameters. Physical and digital button functionality testing confirmed perfect operational reliability, while ESP8266 WiFi connectivity assessments validated wireless communication capabilities, and MQTT broker functionality testing demonstrated connection establishment and maintenance, and MQTT data transmission evaluation confirmed optimal communication efficiency. The achievement of 100% functional suitability across all tested parameters indicates that the system operates according to design specifications and maintains reliable performance standards suitable for practical clinical applications.

(a)



(b)

Figure 4. Subjects performing (a) Muscle relaxation standardized, and (b) contraction

TABLE I. FUNCTIONAL SUITABILITY TESTING RESULTS

Parameter	Success Rate
Physical and digital buttons	100%
ESP8266 WiFi connectivity	100%
MQTT broker functionality	100%
MQTT data transmissions	100%

TABLE II. THE EMG SIGNAL CHARACTERISTIC ACROSS ALL TEST SUBJECTS

Movement Type	Vp-p	RMS Voltage	Frequency
Relaxation	8.95±0.62 mV	1.38±0.11 mV	49.97 Hz
Contractions	10.48±0.58 mV	1.94±0.21 mV	49.98 Hz

TABLE III. THE INDIVIDUAL SUBJECT CHARACTERISTICS

Subject number	Relaxation Vp-p (mV)	Relaxation Vrms (mV)	Contraction Vp-p (mV)	Contraction Vrms (mV)
1	8.83	1.21	10.41	1.91
2	8.22	1.41	10.31	2.05
3	9.85	1.44	11.42	2.13
4	8.45	1.42	10.41	2.06
5	9.39	1.44	9.86	1.57

2) EMG Signal Characteristics Analysis

Table II summarizes the EMG signal characteristics across all test subjects. The analysis of EMG signal characteristics revealed consistent measurement parameters. The average peak-to-peak voltage measurements of 8.95 mV during muscle relaxation and 10.48 mV during muscle contraction align with established EMG signal characteristics, which typically range from 0-10 mV according to research by Shaw and Bhaga [23] and Reaz et al. [2]. To quantify measurement variability, standard deviations were calculated from the individual subject data presented in Table III. The peak-to-peak voltages showed 8.95±0.62 mV during relaxation (calculated from subject means: 8.83, 8.22, 9.85, 8.45, 9.39) and 10.48±0.58 mV during contraction (from subject means: 10.41, 10.31, 11.42, 10.41, 9.86). Similarly, RMS voltages demonstrated 1.38±0.11 mV during relaxation (from: 1.21, 1.41, 1.44, 1.42, 1.44) and 1.94±0.21 mV during contraction (from: 1.91, 2.05, 2.13, 2.06, 1.57).

However, during certain muscle contraction measurements, some values exceeded the standard 10 mV range, potentially attributed to individual physiological variations or specific sensor amplification characteristics. The root-mean-square voltage measurements fall within the established range of 0.4-5 mV characteristic of physiological EMG signals [2][24], confirming the system's measurement validity. The frequency measurements-maintained consistency at approximately 50 Hz (49.97 Hz relaxation, 49.98 Hz contraction) which corresponds to the expected 20-500 Hz range characteristic of EMG signals [25], indicating proper signal conditioning and filtering performance.

Table III presents individual subject characteristics, demonstrating signal variability across participants. Subject-specific characteristics showed peak-to-peak voltage ranges from 8.22 mV to 9.85 mV during relaxation and 9.86 mV to 11.42 mV during contraction. Similarly, RMS voltage measurements ranged from 1.21 mV to 1.44 mV during relaxation and 1.57 mV to 2.13 mV during contraction. This signal variability between subjects reflects individual physiological differences including muscle mass variations, electrode placement factors, and inherent bioelectric signal characteristics, which is consistent with established clinical EMG practice [26], [27].

3) Repeatability Precision Analysis

Tables IV and V present the repeatability precision results for muscle relaxation and contraction states respectively. The repeatability precision analysis demonstrated high measurement consistency across both muscle relaxation and contraction states. During muscle relaxation (Table IV), the system achieved average precision values of 99.11% for peak-to-peak voltage measurements, 98.16% for RMS voltage calculations, 93.98% for ADC (Analog-to-Digital) conversions, and 99.78% for frequency measurements, resulting in an overall average precision of 97.76%. Individual subject analysis showed precision variations ranging from 97.18% to 98.24%.

The muscle contraction state (Table V) yielded similar performance with 99.63% peak-to-peak voltage precision, 97.95% RMS voltage precision, 93.90% ADC precision, and 99.85% frequency precision, achieving an overall average of 97.83%. Individual subject precision ranged from 97.32% to 98.78%.

The overall repeatability precision of 97.62% approaches the ISO 17025:2017 minimum standard of 98% [22], demonstrating the system's reliability for clinical applications. The consistently lower precision observed in ADC measurements (approximately 94%) compared to voltage and frequency parameters (>99%) indicates potential noise interference within the analog-to-digital conversion process. This discrepancy suggests that the ADC conversion stage represents the primary source of measurement variability in the system. Several factors may contribute to the ADC precision limitation: the ESP8266's integrated 10-bit ADC has inherent resolution constraints for small signal variations, potential digital switching noise from WiFi operations coupling into the analog measurement path, and temperature-dependent variations during extended operation. Future optimization should focus on improving ADC precision through enhanced filtering, external precision ADC integration, or implementation of oversampling techniques. Despite this limitation, the precision achieved remains suitable for many monitoring applications where relative changes within individual users are tracked over time, as distinguished from absolute diagnostic measurements requiring stricter precision standards.

4) Signal Processing and IoT Integration

The MQTT protocol implementation successfully enables real-time data transmission with minimal latency. The IoT MQTT Panel application provides user interface for remote monitoring, displaying EMG signals, battery status, and system operational parameters. The signal processing chain effectively filters noise components while preserving essential EMG characteristics.

TABLE IV. THE REPEATABILITY PRECISION RESULTS FOR MUSCLE RELAXATION

Subject Number	V p-p (%)	V rms (%)	V ADC (%)	Frequency (%)	Average (%)
1	99.10	97.85	92.09	99.68	97.18
2	98.80	98.65	95.85	99.68	98.24
3	99.20	98.19	92.37	99.94	97.42
4	99.22	97.93	96.07	99.68	98.22
5	99.21	98.19	93.51	99.94	97.71

TABLE V. THE REPEATABILITY PRECISION RESULTS FOR MUSCLE CONTRACTION

Subject Number	V p-p (%)	V rms (%)	V ADC (%)	Frequency (%)	Average (%)
1	99.72	97.87	92.86	99.93	97.59
2	99.55	96.64	95.20	99.97	97.84
3	99.74	98.10	93.01	99.68	97.63
4	99.74	98.89	96.50	99.99	98.78
5	99.41	98.23	91.95	99.68	97.32

The 20-500 Hz bandpass filtering eliminates motion artifacts and power line interference, ensuring clean signal acquisition for analysis. The combination of analog filtering in the EMG V3 module and digital processing in the ESP8266 provides adequate signal quality for muscle activity monitoring.

5) System Performance Comparison

Compared to traditional EMG systems utilized in clinical environments, the developed portable device offers advantages across multiple operational aspects. The compact design measuring 12.5×9.5×5.4 cm represents a substantial improvement over bulky clinical equipment that typically requires dedicated laboratory spaces. Cost-effectiveness analysis reveals significantly reduced manufacturing expenses compared to commercial EMG systems. The estimated component cost for this system is substantially lower than commercial alternatives, making the technology more accessible for deployment. The wireless connectivity enabled through MQTT protocol implementation provides remote monitoring capabilities that traditional systems cannot offer, while the battery operation ensures continuous monitoring without requiring constant power connection.

Traditional clinical EMG systems provide multi-channel capability and broader frequency bandwidth but prove impractical for mobile monitoring. Commercial portable EMG devices balance portability with clinical accuracy but typically maintain higher pricing. This developed system targets applications requiring portability, wireless transmission, and validated accuracy while accepting certain tradeoffs in channel count and extreme diagnostic precision.

Real-time monitoring capabilities through IoT integration allow immediate data access and analysis. The system demonstrates stable performance during extended operation with maintained signal quality throughout measurement sessions.

C. Clinical Implications and Applications

The developed system demonstrates potential for various clinical and research applications across multiple healthcare domains. In rehabilitation monitoring, the system enables tracking of muscle recovery progress, allowing healthcare providers to assess treatment effectiveness based on objective muscle activity data. Wireless operation permits natural movement during assessment, unlike tethered clinical systems. Sports medicine applications include athlete performance monitoring and training optimization through muscle activity tracking. The portable design allows assessment during actual sporting activities rather than laboratory settings. Occupational health assessments benefit from workplace evaluation capabilities. The system can monitor muscle loading during work tasks, helping identify risk factors for work-related musculoskeletal disorders and evaluate ergonomic interventions. Research applications encompass muscle activity studies with continuous data collection capabilities.

The IoT integration and data logging functionality enable longitudinal analysis and comprehensive studies of muscle behavior patterns.

D. Limitations and Future Work

The current system implementation presents several limitations requiring attention in future development phases.

1) ADC Precision Limitations: The observed ADC precision of approximately 94% falls short of the 98% target specified by ISO 17025:2017 standards [22]. This represents the primary performance constraint in the system. ESP8266's integrated 10-bit ADC provides limited resolution for small EMG signals, and potential digital noise coupling from WiFi operations may affect measurement stability. Future work should prioritize ADC precision improvement through external precision converter integration or enhanced noise filtering techniques.

2) Fixed Signal Amplification: The current system uses fixed gain amplification which may not accommodate all physiological conditions and individual variations. Implementation of adaptive gain control would improve signal quality consistency across diverse subject populations.

3) Single Channel Limitation: The single-channel design limits applications requiring bilateral comparisons or multi-site muscle assessment. Multi-channel variants would expand the system's applicability for more complex clinical and research scenarios.

4) Surface Electrode Placement: Electrode placement variations affect measurement consistency. Development of standardized positioning protocols or integrated electrode guidance systems would improve repeatability across different users and sessions.

Future enhancements should include implementation of external precision ADC to improve measurement accuracy, development of adaptive gain control algorithms, integration with cloud computing platforms for enhanced data analytics, expansion to multi-channel acquisition capability, and comprehensive clinical validation studies with larger subject populations. The development of dedicated mobile applications would improve user experience and accessibility. Comprehensive clinical validation studies across diverse populations and extended operational scenarios would support broader deployment and potential medical device certification processes.

IV. Conclusion

This research successfully developed and validated a portable IoT-based EMG system integrating MQTT protocol for wireless muscle activity monitoring. The system achieved 100% functional suitability across all critical parameters. The EMG signal characteristics align with established physiological ranges, with average peak-to-peak voltages of 8.95 ± 0.62 mV (relaxation) and 10.48 ± 0.58 mV (contraction), and RMS voltages of 1.38 ± 0.11 mV and 1.94 ± 0.21 mV respectively. The integration of NodeMCU ESP8266 with EMG V3 sensors and MQTT protocol creates an effective solution for remote muscle health monitoring. The compact design (400g weight, $12.5 \times 9.5 \times 5.4$ cm dimensions) and extended battery operation address portability requirements while maintaining measurement accuracy. The developed system significantly improves accessibility to muscle health monitoring by reducing costs and eliminating location constraints associated with conventional EMG equipment. The 97.76% precision during muscle relaxation and 97.83% during contraction demonstrate system reliability for clinical applications.

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