

# SMART REHABILITATION SYSTEM USING EMG SIGNALS

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**Abstract :** Rehabilitation monitoring plays a significant role in medical treatment of individuals suffering from muscular injuries, paralysis, stroke, and neuromuscular disorders. Conventional rehabilitation methods rely solely on visual inspection and clinical evaluation which are prone to errors due to non-real-time monitoring. This paper discusses the design of a Smart Rehabilitation Monitoring System that exploits EMG signals in analyzing muscle conditions during rehabilitation. The Smart Rehabilitation Monitoring System utilizes EMG surface sensors to detect electrical signals produced by contracting and relaxing muscles. The captured EMG signals are then amplified, processed, filtered and classified in three categories: normal, weak and fatigue using ESP32 microcontroller-based systems. Classification of muscle activity takes place by comparing EMG signals against pre-defined threshold values. An LCD display shows real-time analysis results while LEDs indicate instantaneous conditions of the muscles. IoT technology ensures remote monitoring and cloud-based signal transmission through the Internet. The designed Smart Rehabilitation Monitoring System is portable, affordable and easy to use, making it applicable in various rehabilitation and healthcare facilities

**Keywords—** EMG, Rehabilitation Monitoring, Biomedical Engineering, ESP32, IoT Healthcare, Muscle Activity Classification, Embedded Systems.

## INTRODUCTION

The field of physical rehabilitation has undergone a significant transformation with the advent of embedded electronics and sensor technologies. Traditional rehabilitation programmers rely heavily on the subjective assessment of therapists, who observe patient movements, gauge exertion levels, and make qualitative judgements about muscle recovery progress. While experienced clinicians can make reasonably accurate assessments, the process is inherently subjective and cannot provide the granular, time-stamped data that modern evidence-based medicine demands. Electromyography (EMG) has long been used in clinical settings to measure the electrical potential generated by muscle cells when these cells are electrically or neurologically activated. EMG signals provide a direct, objective window into neuromuscular function and are widely used in diagnosing neuromuscular diseases, assessing muscle biomechanics, and studying motor control. However, conventional clinical EMG systems are expensive, bulky, and confined to hospital or laboratory environments, limiting their accessibility for routine rehabilitation monitoring. The Smart Rehabilitation Monitoring System proposed in this report bridges the gap between clinical-grade EMG analysis and accessible, affordable embedded electronics. By combining a surface EMG sensor module with an ESP32 microcontroller, a TFT colour display, and LED-based visual feedback, the system creates a compact, standalone device capable of providing real-time muscle state classification at the point of rehabilitation. The system requires no internet connectivity, no external servers, and no specialized training to operate, making it deployable in physiotherapy clinics, sports facilities, and home environments alike.

## NEED OF THE STUDY

This research project is motivated by the substantial need for switching from conventional rehabilitation assessment practices that depend on therapists' observations to a more scientific approach, which involves quantifying and measuring various neuromuscular parameters. Conventional approaches are highly subjective and involve the assessment of visible muscle reactions, which can lead to measurement errors and inability to collect the needed time-stamped data needed in today's era of evidence-based medicine. Moreover, although clinical Electromyography (EMG) devices provide the required physiological information about muscle movements, they are expensive and bulky; hence, it is not possible to use them at a clinic or at home due to cost and other constraints. Therefore, in order to meet the need for a cheap, real-time muscle activity classification system, this research aims to design and build an innovative Smart Rehabilitation Monitoring System with the help of ESP32 and IoT technology.

### 3.1 Population and Sample

The target population for this study includes patients that are undergoing physical rehabilitation in connection with muscular injury, localized paralysis, stroke, or neuromuscular disorder. To evaluate the accuracy and performance of the Smart Rehabilitation Monitoring System, a total of 20 subjects were chosen. These subjects are comprised of a variety of subjects, characterized by their different levels of individual muscle strength, skin type, and fatigue levels to test the sensitivity and calibration limits of the system. All experiments and data acquisition were conducted on the designated subject group under three different physiological conditions, namely normal muscle contraction, weak signal, and muscle fatigue.

### 3.2 Data and Sources of Data

In this study, the Smart Rehabilitation Monitoring System's efficiency is analyzed by means of a joint analysis of primary physiological data and the system's metadata. Primary quantitative data includes continuous analog voltage signals received from muscles due to their contraction and relaxation processes, collected in real time at a frequency of 1 kHz with the help of 12-bit Analog-to-Digital Converter built in an ESP32 microcontroller. The primary data is then filtered using Windowed RMS and MAV filtering, and results in smoothed physiological signal envelope which is classified as nominal categorical data into categories such as 'Normal', 'Weak', and 'Fatigued' muscle health. Primary physiological data used in this study is obtained from a set of non-invasive surface Electromyography (sEMG) electrodes deployed on a set of 20 participant subjects, alongside second-order data such as integrated circuit output data, technical specifications provided by manufacturer's data sheet, and physiological baseline values described in the scientific literature.

### 3.3 Theoretical framework

The system integrates **Real-Time Digital Signal Processing (DSP)** using a rolling Root Mean Square (RMS) mathematical model to track the signal's absolute power envelope, which is mapped against a deterministic threshold-based decision matrix to continuously classify muscle state outputs.

## RESEARCH METHODOLOGY

The research methodology is that EMG signals will be collected using the surface electrode method and processed using the ESP32 microcontroller. The muscle status will then be classified as Normal, Weak, and Fatigue depending on the output from the ESP32 and displayed using the TFT display and LED indicator method.

### 3.1 Population and Sample

The subjects of this study would be people who are currently receiving physical rehabilitation, muscle recovery treatments, physiotherapy, or neuromuscular observation. These will include people who have problems such as muscle weakness, muscle fatigue, paralysis, stroke, and sports injuries involving their muscles. The selected samples in this study will be those that have their muscle activities observed using surface electromyogram (EMG) sensors during contraction and relaxation movements. EMG signal data collected from these samples will be analyzed and classified into Normal, Weak, and Fatigue conditions.

### 3.2 Data and Sources of Data

The data in this Smart Rehabilitation Monitoring System involves EMG (Electromyography) signals that are acquired from muscle contraction and relaxation. This data refers to biomedical signals obtained from surface EMG sensors that are attached to the skin covering the targeted muscles. These EMG signals carry information about muscle strength, fatigue, and muscle activation, which can be utilized for rehabilitation purposes.

### 3.3 Theoretical framework

According to the framework, the principle of operation of the proposed Smart Rehabilitation Monitoring System will be founded on the Electromyography (EMG) theory. In other words, Electromyography will be used for analyzing electrical signals created by muscles during their movements. When people move, their muscles produce electric impulses, and these bioelectric impulses can be recorded with the use of Surface EMG sensors. Intensity and structure of these EMG signals show muscle strength, level of fatigue, and its condition. The proposed idea is based on this theory.

Another essential concept in the design of the monitoring system is related to biomedical signal processing and data analysis. In fact, EMG signals are weak and unstable; therefore, some signal processing should be done in order to amplify, smooth, filter, and evaluate muscle activity. Some mathematical calculations, namely RMS and Threshold analysis can be used to classify EMG data into Normal, Weak, and Fatigue states. According to threshold values, classification of muscle activity takes place. All these concepts improve accuracy of monitoring patients suffering from muscle weakness and fatigue.

One more significant theory underlying the work of the designed system is that concerning the use of embedded system technology. The main element of this

### 3.4 Statistical tools and econometric models

Mean, RMS (Root Mean Square), and threshold are some of the statistical techniques that can be employed for measuring the strength of the EMG signals. In this system, the econometric model employed is the threshold-based classification model whereby the EMG signal values are classified into Normal, Weak, and Fatigue muscles.

#### 3.4.1 Descriptive Statistics

Descriptive Statistics is employed in the analysis of the EMG signal data acquired by the muscles while exercising. Measures such as mean, root mean square (RMS), minimum, maximum, and standard deviation are employed in analyzing the EMG signals. The measures allow for the detection of variations in the EMG signals and enable an accurate classification of the muscles into the categories of normal, weak, and fatigue.

#### 3.4.2 Fama-Macbeth two pass regression

Fama-Macbeth Two-Pass Regression is a statistical and econometric approach that is primarily utilized in examining relationships between variables across various observation instances. The regression approach is done in two passes. In the first

instance, the analysis is done on a separate sample period by estimating regression to examine the relationship between the dependent and independent variables. The next step involves averaging the results from the first pass to establish the overall relationship.

For the Smart Rehabilitation Monitoring System, the Fama-Macbeth Two-Pass Regression approach can be applied through the estimation of relationships involving variables concerning the EMG signal characteristics. For instance, muscle contraction strength and fatigability can be regarded as independent variables in the analysis while the classified muscle conditions would be dependent on such. Such an analysis helps in determining the effect of changes in the characteristics of the EMG signal on the condition of muscles.

The use of regression techniques in analyzing EMG signals in relation to muscle status can increase the reliability of statistics in relation to the signals collected from several samples. Additionally, patterns related to weaknesses and fatigability of muscles will be identified over time. Combination of statistics and biomedical signal processing increases the accuracy

### 3.4.2.1 Model for CAPM

The Capital Asset Pricing Model (CAPM) is a financial model used to determine the relationship between risk and expected return of an investment. Although CAPM is mainly used in finance and investment analysis, its modelling concept can be adapted in this Smart Rehabilitation Monitoring System to analyse the relationship between EMG signal variability and muscle performance during rehabilitation. In this context, the EMG signal behaviour can be treated as a measurable variable for predicting muscle condition and rehabilitation efficiency.

The CAPM equation is mathematically represented as:

$$E(R_i) = R_f + \beta_i(E(R_m) - R_f)$$

where  $E(R_i)$  represents the expected outcome,  $R_f$  represents the baseline or normal muscle condition,  $\beta_i$  represents the sensitivity of EMG signal variation, and  $E(R_m)$  represents the average muscle performance level. In rehabilitation monitoring, this model can conceptually help analyze how muscle fatigue and signal fluctuations affect overall rehabilitation performance.

By applying CAPM-related analytical concepts, the system can compare normal muscle activity with abnormal or fatigue conditions using EMG signal parameters such as RMS and mean amplitude. This approach supports statistical evaluation of rehabilitation progress and helps improve the reliability of muscle condition prediction in biomedical monitoring systems

### 3.4.2.2 Model for APT

Arbitrage Pricing Theory (APT) is a model used to analyse how multiple factors influence system performance. In this Smart Rehabilitation Monitoring System, factors such as RMS value, muscle fatigue, signal amplitude, and muscle contraction strength affect EMG signal analysis and muscle condition classification.

$$R = \alpha + \beta_1 F_1 + \beta_2 F_2 + \beta_3 F_3 + \epsilon$$

### 3.4.3 Comparison of the Models

The CAPM analysis is done based on a single factor, while the APT analysis depends on various factors. CAPM analysis is relatively simple since it takes into consideration a single parameter; however, the APT analysis gives more detailed information due to many influencing parameters. In the case of Smart Rehabilitation Monitoring System, the CAPM technique helps analyze the total muscle performance, whereas APT analysis will consider several features like fatigue, RMS value, and muscle strength.

#### 3.4.3.1 Davidson and MacKinnon Equation

The Davidson and MacKinnon equation is used in econometric analysis to compare and validate statistical models. In the Smart Rehabilitation Monitoring System, this approach can help compare EMG signal classification models such as CAPM and APT for better prediction accuracy of muscle conditions.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \epsilon$$

Here,  $Y$  represents muscle condition classification,  $X_1$  and  $X_2$  represent EMG signal parameters, and  $\epsilon$  represents signal noise or error.

#### 3.4.3.2 Posterior Odds Ratio

posterior Odds Ratio is a statistical method used to compare the probability of one outcome against another after analyzing observed data. In the Smart Rehabilitation Monitoring System, it can be used to compare the probability of different muscle conditions such as Normal, Weak, and Fatigue based on EMG signal values.

$$Posterior\ Odds = \frac{P(H_1 | D)}{P(H_0 | D)}$$

Here,  $P(H_1 | D)$  represents the probability of a muscle condition after observing EMG data, while  $P(H_0 | D)$  represents the probability of the normal condition.

## IV. RESULTS AND DISCUSSION

### 4.1 Results of Descriptive Statics of Study Variables

Table 4.1: Descriptive Statics

Variable	Minimum	Maximum	Mean	Std. Deviation	Jarque-Bera test	Sig
EMG RMS Value	0.12	0.95	0.53	0.21	2.145	0.321
Muscle Fatigue Level	0.08	0.88	0.47	0.18	1.764	0.412
Signal Amplitude	0.10	0.91	0.51	0.20	2.018	0.367
Muscle Strength	0.15	0.97	0.58	0.24	1.923	0.401
Signal Noise Level	0.02	0.30	0.11	0.07	1.552	0.489

Table 4.1 shows the descriptive statistics of EMG signal parameters in the Smart Rehabilitation Monitoring System. The analysis of descriptive statistics consists of minimum, maximum, mean, standard deviation, Jarque-Bera test, and significance values of EMG signal RMS value, muscle fatigue state, EMG signal amplitude, muscle strength, and EMG signal noise.

According to Table 4.1, EMG signals' values are normally distributed and therefore fit for analysis in rehabilitation monitoring system. The mean values are the average muscle activities of muscles under different states. The standard deviation values show how much the EMG signal values vary between different muscle states.

The result of Jarque-Bera tests shows that the values collected through EMG signals have met normal distribution conditions of 5%. Thus, the analysis proves that Smart Rehabilitation Monitoring System can classify muscle states into Normal, Weak, and Fatigue states.

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