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BIOMEDICAL SIGNAL PROCESSING TECHNIQUES: METHODS, APPLICATIONS, AND CHALLENGES

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ABSTRACT

Biomedical signal processing is a key area within biomedical engineering that is interested in physiological signals acquired from patients. When these signals analyzed and processed can help medical teams to make their optimal decisions. Physiological signals such as electrocardiogram (ECG), electroencephalogram (EEG), electromyogram (EMG) involve valuable data that contribute solving the issues of patients. These physiological signals suffer from noise and artifacts, and require amplification, extraction and processing. This paper provides a comprehensive review about physiological signals their meanings, importance, applications in the healthcare field, and challenges face signal processing. Also, it includes highlights about signal acquisition and some pre-processing approaches required to obtain the useful information from signals.

KEYWORDS: Biomedical Signal Processing, ECG, EEG, EMG.

1. INTRODUCTION

Biomedical signal processing is a significant field in biomedical engineering that applies math, computational techniques, physics, and different engineering aspects to analyze and acquire important information from physiological signals. These bio signals are originated from different organs such as heart, brain, muscles, and blood vessels (Rangayyan and Krishnan 2024).

In fact, physiological signals always have significant issues that might affect the importance of knowledge integrated in these signals. The problems revolve around artifacts, noise, nonlinear, low amplitude, non-stationary physiognomies, and interpersonal variability (Parbat 2023). To solve these issues there is a need to implement high-tech solutions to extract clinically evocative evidence, support diagnosis, monitor patients, guide therapy, and empower the improvement of progressive medical devices and decision-support systems.

Biological signal processing and analysis performances comprise designing signal pre-processing implements for portable wearable sensors (Lin et al. 2022; Maity et al. 2022), artifacts cancellation approaches for signal quality enhancement, nonlinear analysis for demonstrating signal involvedness or dynamics, feature extraction utilizing time-frequency analysis or statistical models, pattern classifications, and computer-aided diagnosis regarding to deep learning neural networks or other computational algorithms.

2. BIOMEDICAL SIGNALS ACQUISITION

Acquisition of biomedical signals is the first and the most important step in bio signal processing. This process involves capturing the different physiological signals from human body using appropriate signals and transducers.

2.1 TYPES OF BIOMEDICAL SIGNALS

Bio signals can be classified into several categories which are.

i. Bio electrical signals: this category involves signals extracted from important organs such as heart, brain, and muscles. In this category, it is significant to measure the small ranges of voltage and current. Here, bio signals are electrocardiogram (ECG) (Ansari et al. 2023), electroencephalogram (EEG) (Weng et al. 2025), and electromyogram (EMG) (Kim et al. 2022).

ii. Bio mechanical signals: signals in this category associated with mechanical movement of the body organ such as blood pressure and respiratory signals (Chandra and Upadhyay 2023).
iii. Bio acoustic signals: signals that are related to sounds' amplitude and wave like heart sounds and lung sounds. In heart, the noises made by the heart's valves closing, commonly heard as "lub-dub" (Gao et al. 2024).
iv. Bio chemical signals: signals associated with levels of solutions, fluids, electrolyte panels, metabolic panels such as glucose levels in blood and oxygen saturation (Guindani et al. 2022).

It is important to mention that each type of bio signals require specific sensors and specialized acquisition methodologies to ensure accurate and reliable measurement.

2.2 CHARACTERISTICS OF BIO SIGNALS

Signals acquired from human body deploys different features that reflect the need to process them carefully. The first feature is the low amplitude which can be seen obviously in EEG. However, EEG signal reflects the brain continuous electrical activity. This signal has an amplitude in the microvolt level range. This characteristic (i.e. low amplitude) requires to be amplified to useful ranges.

Another important characteristic of bio signals is the nonstationary which is defined as the changing of numerical values over time for these signals. Studies always acquire data second by second and/or minute by minute and/or hour by hour and/or any appropriate acquiring time based on the importance of the signal, the medical device software, and the medical team decision (Sarna, Hossain, and Islam 2024).

Nonlinearity is another important feature in bio signals. Here, the bio signal recognizes hidden, multifaceted arrangements, like fractal complexity and state-space attractors, which are serious for identifying diseases, monitoring heart rate variability (HRV), and assessing autonomic nervous system function. Moreover, signals differ dramatically between individuals and even within the same individual over time leading to variability issue. Some signals require to be gathered and monitored continuously since it vary over time (Germán-Salló 2024).

Signals are exaggerated via motion artifacts, electrical interference, muscle movement, and instrumentation noise which lead to noise contamination. This problem needs a multi-layered methodology merging appropriate hardware research, signal preparing, and progressive digital signal processing (DSP) to exploit the signal-to-noise ratio (SNR) (Kalaiarasi et al. 2024).

3. SIGNAL ACQUISITION AND CONDITIONING

Bio signals require sensors and transducers to be acquired from human bodies. Any acquisition system needs important electronic parts such as amplifiers (low pass, high pass, notch), filters, analog to digital converter (ADC), microcontroller, processor, and storage unit. This acquisition system aims to provide significant considerations like sensitivity, frequency response, linearity, biocompatibility, and stability over time (Sestrem et al. 2022; SAMANO-FLORES et al. 2022).

Amplification is required always in bio signals processing. In this step, the minimal values of amperes, voltages, decibels (dbs), and frequencies are maximized to qualified and measurable magnitudes. Moreover, instrument amplifier is the most important used part to do this task. It has dual duties in amplifying weak signals and rejecting common mode noise. These schemes, frequently expending 3-op-amp conformations, serving conditioned signals into digitizers.

Conditioning of bio signals contains sampling and digitizing; where the analog parameters converted into digital ones using ADC. Here, the rate at which an ADC converts analog signals into digital data is measured in samples per second. However, to evade aliasing and guarantee precise reconstruction, the Nyquist-Shannon formula necessitates a sampling rate as a minimum twice the highest signal frequency. Also, the quantization error is needed to be determined. To impact signal reliability, the dynamic range is required to be known.

There are different types of filters that can be used in processing any bio signal and quantify the data integrated in the signal. These filters vary between its characteristics and uses. In fact, filters vary between low-pass filters, high-pass filters, band-pass filters, and notch filters. There are also adaptive filters such as least mean square filters (LMS) and recursive least square filters (RLS). Each of which has its own features and uses (James 2025).

4. CLINICAL APPLICATIONS

There are many different clinical applications after completing the processing of bio signals. Cardiology applications use bio signals in different approaches such as ECG analysis for arrhythmia detection, heart rate variability exploration for autonomic function evaluation, and prediction of deterioration in patients admitted in ICUs and/or general wards. Another application is the neurology field. Here, analysing EEG can be used for epilepsy diagnosis (Giannoni, Gentile, and Passino 2022). Also, it can be used for sleep stage classification. Brain-computer interfaces are another application that utilize bio signals in neurology.

In healthcare, rehabilitation and prosthetics can obtain many benefits from bio signals processing. In this field, most of actual uses of prosthetic control, EMG signals analysis is utilized. The key purpose is low processing and implementation involvedness, also leading to reasonably high accuracy. Further analysis to these signals helps in construction of gait labs which solve many movement issues in patients. Some new approaches show significant advantages in bio feedback systems (AlQahtani, Al-Naib, and Althobaiti 2024).

Continuous monitoring of vital signs is an important area where processing bio signals can be used. This important healthcare field presents serious visions to the medical team and helps them take the right decisions for patients. In this application, detection of abnormalities and prediction of various deteriorations can seriously decrease mortality and increase morbidity (Kristinsson et al. 2022).

5. CRITICAL CHALLENGES

Processing of bio signal face some challenges that might affect the results of this approach. The first challenge is the limited computational resources like low battery life, limited memory that might cannot hold the data acquired, and restricted processing power which affect the real time streaming. Moreover, the need for efficient algorithms and models to solve the dimensionality problem of data (Zhao et al. 2022).

Technologies use bio signal processing must have the feature of robustness to noise and artifacts. As mentioned before, many bio signals have low ranges of amperes, voltages, and frequencies, so acquiring them using high-tech devices and advanced algorithms embedded in machine learning and deep learning should be very sensitive, robust, and able to reject any unnecessary signal (Rahman et al. 2022).

Wearable devices that detect bio signals and process them simultaneously require good battery life usage where it can help patients or users for acceptable time and does not require to charge their batteries all the time. Systems like competent filtering models, optimized feature extraction, and hardware acceleration by means of digital signal processors (DSPs) are normally employed (Stuart, Hanna, and Gutruf 2022).

6. CONCLUSION

Biomedical signal processing is a key component of current healthcare technology, allowing for the extraction of relevant information from complex physiological data. Clinicians and engineers use techniques like filtering, time-domain and frequency-domain analysis, time-frequency approaches, feature extraction, deep learning, and machine learning to diagnose diseases, monitor patients, guide therapy, and design new medical equipment.

As healthcare systems progressively integrate wearable technologies, telemedicine, and artificial intelligence, the need for strong, dependable, and ethical biomedical signal processing will expand. Ongoing research and innovation in this field hold the promise of improving patient outcomes, increasing healthcare efficiency, and facilitating the move to customized and preventative medicine.

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