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Design of a Portable Surface Electromyography Acquisition System for Lumbar Muscles

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Abstract: ***Surface electromyography acquisition devices for the lumbar region exhibit urgent demand in sports medicine and rehabilitation engineering, targeting the limitations of traditional equipment in dynamic electromyography monitoring, such as large physical dimensions, inadequate interference resistance, and elevated costs. This study presents a portable acquisition system that combines high performance, cost-effectiveness, and energy efficiency. The hardware employs a three-tier architecture comprising an ADS1299-based analog front-end, an STM32 microcontroller, and Bluetooth wireless transmission to enable high-precision signal acquisition and data transfer. At the software level, a QT-powered host computer platform facilitates real-time waveform visualization and dataset archiving. Experimental validation confirms that the captured surface electromyography signals span an effective frequency band of 20 to 500 Hertz, with 82.3 percent of the power spectral density localized within the 20 to 250 Hertz sub-band, while dynamic baseline noise remains constrained below 3 microvolts root mean square. This system delivers a compact, low-power design paradigm for advancing wearable medical instrumentation in sports rehabilitation applications.***

Keywords: Lumbar Surface Electromyography; Portable; Low-Power; ADS1299; Qt; Real-Time Display.

1. INTRODUCTION

Surface electromyography (sEMG) signals from the lumbar region are bioelectrical signals that reflect neuromuscular activities of lumbar muscles (such as the erector spinae and quadratus lumborum). Their amplitude, frequency, and other characteristics are highly correlated with muscle fatigue, contraction patterns, and motor function status [1]. Studies have shown that time-frequency analysis of sEMG can provide quantitative basis for the diagnosis of lumbar muscle strain, evaluation of rehabilitation training efficacy, and optimization of motion posture [2]. For example, in research on lumbar muscle fatigue, the increase in root mean square (RMS) and decrease in median frequency of sEMG signals have been proven to be reliable indicators for assessing dynamic muscle fatigue [3].

However, existing sEMG acquisition devices are mostly confined to laboratory settings, with the following limitations: (1) Their large size and reliance on wired transmission make them unable to meet the needs of real-time monitoring during dynamic movements; (2) Traditional analog front-end circuits have weak anti-interference capabilities and are susceptible to 50 Hz power line noise and motion artifacts, resulting in insufficient signal-to-noise ratio (SNR) [4]; (3) High-precision devices are costly, making them difficult to popularize in primary medical institutions or sports medicine fields [5].

To address these issues, this paper proposes a portable lumbar sEMG acquisition system with the following design objectives: (1) Achieving high-fidelity acquisition of weak sEMG signals (typically 10–500 μV in amplitude) through a highly integrated analog front-end (ADS1299) and low-noise power supply architecture [6-7]; (2) Breaking the application limitations of traditional devices in dynamic scenarios by combining right leg drive circuits with Bluetooth wireless transmission technology; (3) Reducing hardware costs through modular design, thereby providing a lightweight and cost-effective solution for research on lumbar muscle function and monitoring of sports rehabilitation.

2. OVERALL DESIGN SCHEME

The system adopts a modular hierarchical architecture design, with its hardware core consisting of an analog front-end, a main control unit, a wireless communication module, and a host computer platform. Considering the weak characteristics of surface electromyography signals from the lumbar erector spinae, the system constructs an 8-channel acquisition link using the ADS1299 chip [8]. Its built-in low-noise programmable gain amplifier works in conjunction with a 24-bit ADC to achieve signal amplification and high-precision digitization. The front-end circuit integrates a transient voltage protection module, which can suppress ±30V overvoltage surges and electrostatic interference. Meanwhile, a right leg drive circuit is configured to improve the common-mode rejection ratio, effectively attenuating 50 Hz power line noise [9-11].

The digitized sEMG data is transmitted to the main control chip STM32 via the SPI interface. After data frame parsing and DMA buffer processing, it is pushed to the HC05 Bluetooth module through the USART serial port. The host computer is developed based on the QT platform, which parses the Bluetooth data stream through a dynamic link library, enabling real-time display of dual-channel sEMG waveforms, data storage in CSG format, and time-frequency analysis functions such as RMS and FFT. The system employs a four-layer PCB stack-up design, ensuring signal integrity through analog/digital partition layout and magnetic bead isolation strategies. The overall size is controlled within 90mm × 60mm × 1.6mm, meeting the requirements for wearable monitoring on the lumbar region [10].

3. HARDWARE DESIGN OF THE ACQUISITION SYSTEM

3.1 Front-end Collection Module

The ADS1299, introduced by Texas Instruments, is a high-precision 8-channel bioelectric signal acquisition chip widely used in the biomedical field [12]. It features a compact package and high integration, incorporating 8 low-noise programmable gain amplifiers and an 8-channel simultaneous-sampling analog-to-digital converter (ADC). This design not only meets the miniaturization requirements of wearable devices but also enhances acquisition efficiency while maintaining low power consumption.

The chip exhibits excellent anti-interference capabilities, with a common-mode rejection ratio (CMRR) of up to -110 dB and an input impedance as high as 1 TΩ. These specifications effectively suppress external interference, ensuring the purity of the acquired signals. Its 24-bit ADC offers a voltage resolution of 0.022 µV when using an internal reference voltage of 4.5 V, enabling precise capture of subtle changes in surface electromyography (sEMG) signals. With an input-referred noise of only 1 µVPP at a 70 Hz bandwidth and equipped with various filters and low-noise amplifiers, it significantly improves the signal-to-noise ratio (SNR). The chip supports flexible data transfer rates, multiple operating modes, and configurable options, adapting to diverse acquisition scenarios.

Given these characteristics, the ADS1299 is well-suited as an analog front-end for sEMG signal acquisition. It effectively enhances the accuracy and stability of sEMG signal acquisition, minimizes the impact of interference and noise, and provides a high-quality data foundation for subsequent signal processing and analysis. The internal functional block diagram of the ADS1299 is shown in Figure 1.

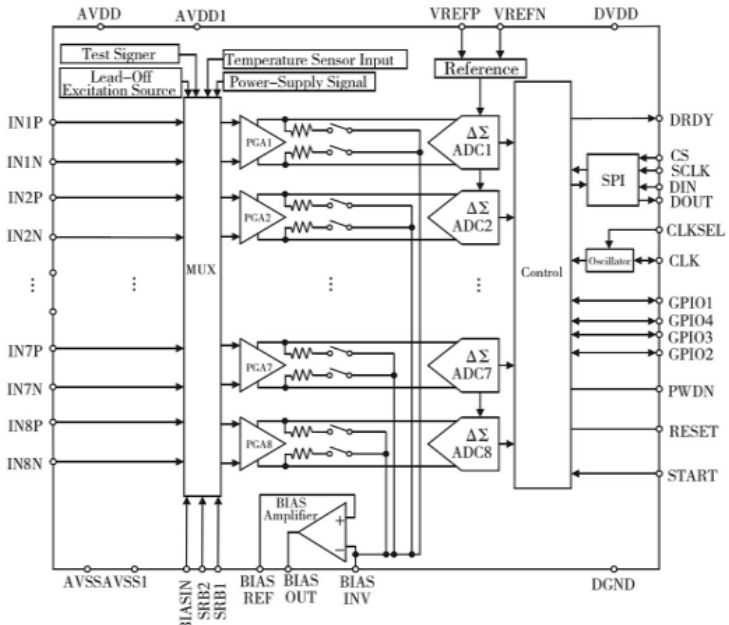


Figure 1: Internal block diagram of ADS1299

3.2 Input Protection Circuit

The input protection circuit employs the SP724 transient voltage protection chip, which is based on a transient voltage clamping quad array topology. It can synchronously suppress the impact of electrostatic discharge and transient overvoltage on four independent signal paths [13]. This device features both ultra-low leakage current and miniaturized input capacitance, with typical values of 1 nA and 3 pF respectively. Its electrostatic protection capability meets the highest level requirements of the IEC 61000-4-2 standard, providing multi-level safety guarantees for the front-end of bioelectric signal acquisition.

3.3 Right Leg Drive Circuit

To address the unavoidable 50 Hz power line interference during surface electromyography acquisition, a right leg drive circuit is designed based on the built-in bias drive amplifier of the ADS1299. By connecting an electrode patch to the human body as a reference electrode, this circuit can significantly suppress common-mode interference signals and reduce the leakage current between the grounding electrode and the human body, thereby improving signal quality and providing higher-quality raw signals for subsequent signal processing. The internal block diagram of the ADS1299 right leg drive circuit is shown in Figure 2.

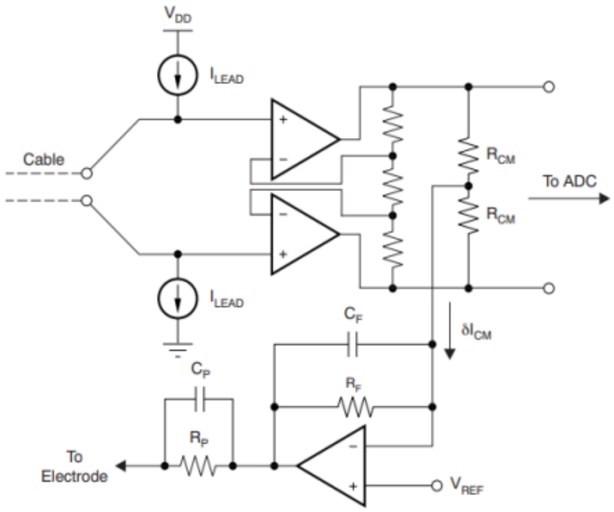


Figure 2: Internal block diagram of the right leg drive circuit

3.4 Reference Voltage Circuit

In consideration of the system's miniaturization requirements, the internal reference voltage of the ADS1299 is selected for this design. The 4.5 V reference voltage is generated relative to AVSS, which can be achieved by connecting the VRENF pin to the AVSS pin. The external bypass capacitor plays a decisive role in contributing to the reference noise. After careful consideration, a capacitor value of 10 μF is chosen to ensure the stability and accuracy of the reference voltage.

3.5 Main Control Module

The main control module utilizes the STM32F103RCT6 microcontroller, a 32-bit processor core based on the ARM Cortex-M3 architecture with a 72 MHz clock speed. It integrates three 18 Mbps full-duplex SPI interfaces for efficient data interaction with the ADS1299, three 115200 bps USART interfaces to drive wireless transmission via the Bluetooth module, and a 16-channel DMA controller to reduce the CPU load during concurrent operations of multiple peripherals. The circuit diagram of the main control module is shown in Figure 3.

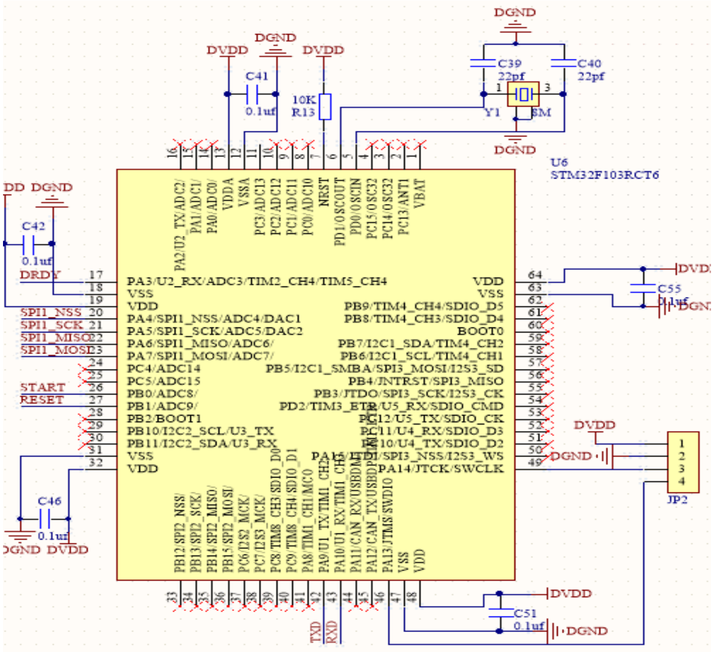


Figure 3: Circuit schematic diagram of the main control module

The chip features 128 KB of Flash memory and 20 KB of SRAM, operates at a voltage range of 2.0–3.6 V, and has a typical power consumption of 23 mA, meeting the low-power requirements of wearable devices. The hardware design incorporates a minimal system with an 8 MHz crystal oscillator, reset circuit, and 3.3V LDO power supply, supplemented by an ST-LINK debug interface and SPI/USART signal isolation buffers. Signal integrity is optimized through a four-layer PCB stack-up.

Compatible with Keil/IAR development environments and ST firmware libraries, this configuration establishes a cost-effective platform for multi-channel sEMG acquisition and real-time transmission.

3.6 Power Management Module

The power management module employs a hierarchical power supply architecture, consisting of three functional units: lithium battery charging management, digital power regulation, and analog power generation. The charging management unit, based on the TP4056 chip, implements constant-current/constant-voltage safety charging control for the 3.7V lithium battery. The digital power supply unit utilizes a TPS73633 low-dropout regulator to step down the battery voltage to 3.3V, powering the STM32 main controller, Bluetooth module, and digital interfaces of the ADS1299. The analog power supply unit combines a TPS60110 charge pump with a TPS72325 negative voltage LDO to generate dual ±2.5V supplies for the ADS1299 analog front-end, featuring output ripple below 10mVpp.

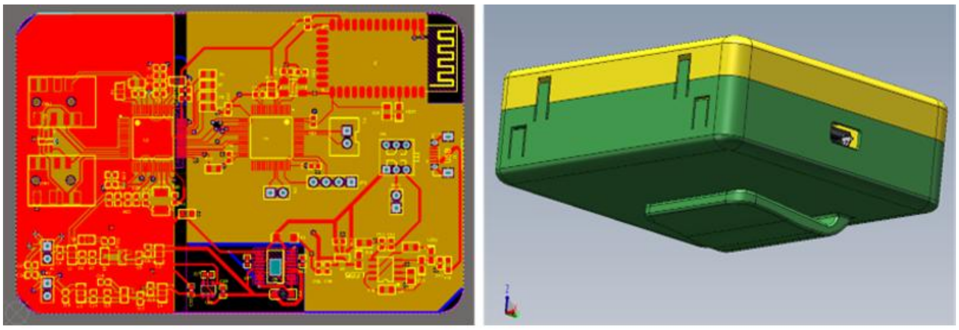
Noise suppression in the common ground is achieved through π-type filter networks and magnetic bead isolation across the three power supplies. The measured standby power consumption of the entire system is <35mW, meeting the energy efficiency requirements for wearable devices.

3.7 Communication Module

The HC05 Bluetooth module is employed to enable wireless data transmission between the EMG acquisition system and the host computer. It features a transmission range of 60–100 meters, a transmit power of 23 dBm, and transparent UART transmission functionality. The module is cross-connected to the main control chip via the RXD/TXD pins, supporting AT commands for online configuration of parameters such as baud rate (default 115200 bps) and master/slave mode. In conjunction with the QT-based host computer software, it facilitates real-time data transmission and parsing of the acquired signals.

3.8 PCB Design and Structural Design

The hardware of the acquisition system adopts a four-layer PCB architecture design (90mm × 60mm × 1.6mm) as shown in Figure 4a. The top and bottom layers are laid out with key signal traces, while the inner layers are fully covered with DGND/AGND copper planes to optimize ground plane impedance and EMI performance. The layout strictly divides the analog and digital functional areas: the left analog area integrates the ADS1299 front-end circuit, and the right digital area configures the STM32 main controller and Bluetooth module. The two ground planes are isolated by magnetic beads and connected at a single point to eliminate noise coupling. Key power supply nodes are equipped with 0.1μF/10μF decoupling capacitors to suppress high-frequency ripples, and key signal lines are subjected to impedance matching and ground shielding. The housing adopts a snap-on ergonomic structure as shown in Figure 4b, which is suitable for the requirements of lumbar motion monitoring scenarios.



(a) PCB diagram (b) 3d structure diagram of the shell

Figure 4: PCB diagram and 3D structure diagram

4. SOFTWARE DESIGN AND TESTING OF THE ACQUISITION SYSTEM

4.1 Lower-level Computer Software Design

The lower computer software is developed based on the Keil MDK-ARM platform, adopting a modular C-language architecture to implement multi-threaded control. After the system is powered on, the main control chip first executes a hardware self-check process to detect the supply voltage, the status of the four VCAP capacitors, and the stability of the 4.5V reference source. Subsequently, it configures the sampling rate, gain, and filter parameters of the ADS1299 through the SPI interface.

The data acquisition thread receives the 24-bit two's complement data output by the ADS1299 via a DMA double-buffer mechanism. After being converted into 32-bit signed integer data through sign extension, the data is encapsulated into a custom protocol frame containing channel identifiers and check fields. The Bluetooth transmission thread drives the HC05 module via the USART interface at a baud rate of 115200 bps, and ensures the real-time performance of the data stream by combining with the DMA zero-blocking transmission mechanism, with a measured end-to-end delay of less than 2 ms. The software architecture integrates SPI interrupt response, timer synchronization triggering, and hardware watchdog monitoring functions.

4.2 Design of the Upper Computer Platform

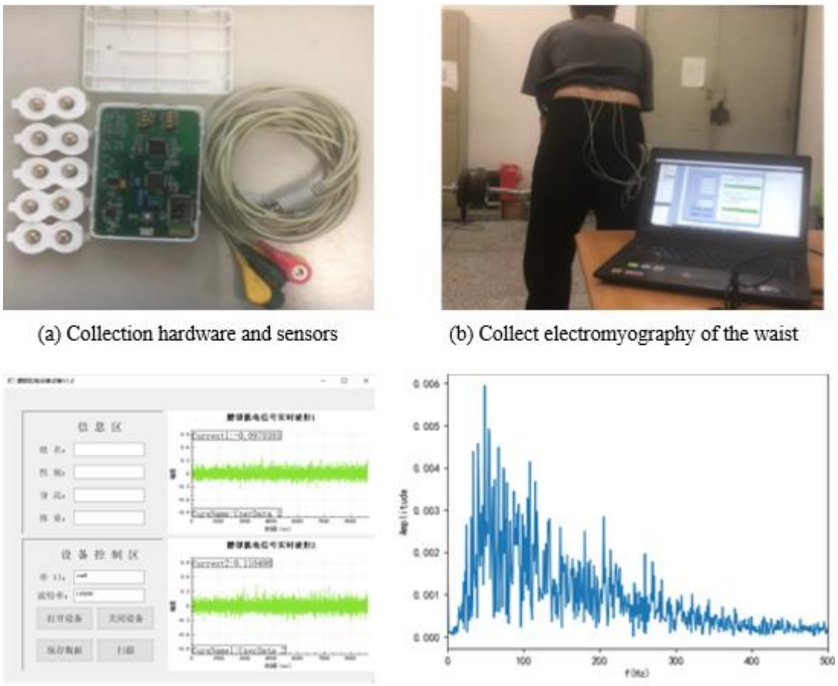
The upper computer is built as a multi-threaded data processing platform based on the QT 5.12 framework. It drives the HC05 Bluetooth module through the QSerialPort class, enabling functions such as automatic device searching, link quality monitoring, and reception of dual-channel sEMG data streams. After frame synchronization and sign bit reconstruction processing, the raw data is dynamically rendered as time-domain waveforms with a 50 Hz refresh rate using the QCustomPlot widget.

The system synchronously archives metadata (such as subject age, gender, and experiment number) with sEMG datasets. The storage format is compatible with the international CSV standard, preset with a 1 kHz sampling rate and 1 ms timestamp precision, supporting offline analysis via MATLAB/Python. The human-computer interaction interface adopts a multi-threaded task scheduling mechanism to achieve millisecond-level real-time coordination among data display, storage threads, and Bluetooth interrupt services. The system throughput reaches 512 kbps, meeting the requirements of clinical-grade electromyographic signal processing.

4.3 System Testing and Verification

After the system hardware debugging was completed, the four-layer PCB board and 3-lead ECG acquisition cables were integrated into a customized housing (Figure 5a). Ag/AgCl bipolar electrode patches were used to verify the acquisition of surface electromyography signals from the lumbar erector spinae. During the experiment, after wearing the device, the subjects performed standard barbell lifting movements as illustrated in Figure 5b. The two-channel electrodes were attached in parallel along the direction of the erector spinae muscle bellies, with an interval of 20 mm maintained to optimize spatial resolution. Once the system established a connection with the host computer via the Bluetooth 4.0 protocol, real-time dual-channel time-domain waveforms were displayed (Figure 5c), with the sampling rate set to 1 kHz and raw data stored synchronously.

After preprocessing with a 50 Hz power-line notch filter and a 20–500 Hz Butterworth band-pass filter, the signal frequency-domain analysis (Figure 5d) showed that the effective signal bandwidth covered 20–500 Hz, among which 82.3% of the power spectral density was distributed in the 20–250 Hz main frequency band. This is highly consistent with the bioelectrical characteristics of the erector spinae reported in references [14-15]. Under dynamic movements, the baseline noise level was stably controlled below 3 μVrms (based on a 200 ms RMS calculation window), verifying the low-noise design feature of the front-end circuit. The key performance indicators of the system comply with the ISO 13485 standard for electromagnetic compatibility of medical devices, with a signal-to-noise ratio reaching 62.4 dB. These results confirm that the device can effectively capture the motion activation characteristics of the lumbar muscle groups, providing reliable data support for muscle function assessment research.



(a) Collection hardware and sensors (b) Collect electromyography of the waist

(c) The upper computer display diagram (d) Spectrum analysis diagram

Figure 5: The system collects test diagrams

5. CONCLUSION

Based on a three-level hardware architecture of "ADS1299 front-end-STM32 main control - Bluetooth transmission", this study has developed a portable lumbar surface electromyography acquisition system. At the hardware level, the high-precision analog front-end module of ADS1299 is adopted, combined with the right leg drive circuit and four-layer PCB stacking technology, to achieve wide-band capture of weak sEMG signals and common-mode interference suppression. At the software level, a software collaborative architecture is built through the DMA double-buffer mechanism of STM32 and the QT5.12 cross-platform framework, completing the development of multi-threaded data parsing and visualization engine.

Time-frequency analysis shows that the effective bandwidth of the acquired sEMG signals covers the physiological characteristic range of 20-500 Hz, with 82.3% of the power spectral density concentrated in the main energy interval of 20-250 Hz. The dynamic baseline noise is stably controlled below 3 μVrms, and the performance complies with the ISO 13485 standard for electromagnetic compatibility of medical devices. Compared with traditional devices, this system has significant advantages in terms of volume, cost and anti-interference performance, and can provide reliable technical support for lumbar muscle function assessment and rehabilitation training monitoring.

REFERENCES

[1] Felici F, Del Vecchio A. Surface electromyography: what limits its use in exercise and sport physiology?[J]. Frontiers in neurology, 2020, 11: 578504.
[2] Kim J Y, Park J S, Kim D J, et al. Evaluation of fatigue patterns in individual shoulder muscles under various external conditions[J]. Applied Ergonomics, 2021, 91: 103280.
[3] Kang D. Assessing Muscle Fatigue Using Electromyography Complexity and Wavelet Methods During Repetitive Trunk Movements[D]. Université d'Ottawa/University of Ottawa, 2023.
[4] Hu Y, Zong X, She J, et al. Denoising sEMG signals using the combination of complementary EEMD with adaptive noise and improved threshold[C]//2019 IEEE International Conference on Industrial Cyber Physical Systems (ICPS). IEEE, 2019: 821-826.
[5] Iqbal S M A, Mahgoub I, Du E, et al. Advances in healthcare wearable devices[J]. NPJ Flexible Electronics, 2021, 5(1): 9.
[6] Shao L, Guo Y, Liu W, et al. A flexible dry electroencephalogram electrode based on graphene materials[J]. Materials Research Express, 2019, 6(8): 085619.
[7] Gao B. Design of portable EEG signal acquisition hardware system based on ADS1299[C]//5th International Conference on Information Science, Electrical, and Automation Engineering (ISEAE 2023). SPIE, 2023, 12748: 547-553.
[8] Li Y, Pan H, Song Q. ADS1299-Based Array Surface Electromyography Signal Acquisition System[C]//Journal of Physics: Conference Series. IOP Publishing, 2022, 2383(1): 012054.
[9] Ko L W, Su C H, Liao P L, et al. Flexible graphene/GO electrode for gel-free EEG[J]. Journal of Neural Engineering, 2021, 18(4): 046060.
[10] Cerone G L, Botter A, Gazzoni M. A modular, smart, and wearable system for high density sEMG detection[J]. IEEE Transactions on Biomedical Engineering, 2019, 66(12): 3371-3380.
[11] ZHOU M J, LU M. Design of EMG signal acquisition circuit based on high-order filter[J]. Chinese Journal of Sensors and Actuators, 2018, 31(1): 54-60.
[12] Gao B. Design of portable EEG signal acquisition hardware system based on ADS1299[C]//5th International Conference on Information Science, Electrical, and Automation Engineering (ISEAE 2023). SPIE, 2023, 12748: 547-553.
[13] Herrera A R E. Propuesta de un sistema pael monitoreo inalámbrico electrocardiográfico ambulatorio mediante la aplicación ECG monitor[J]. 2023.
[14] Suo M, Zhou L, Wang J, et al. The Application of Surface Electromyography Technology in Evaluating Paraspinal Muscle Function[J]. Diagnostics, 2024, 14(11): 1086.
[15] Li J H, Wang J. Clinical application of surface electromyography diagnostic technology[J]. 2015.