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Designing Minimalistic Powered Arm Orthosis for Brachial Plexus Injuries

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Elbow paresis, often resulting from brachial plexus injury, presents a significant challenge in the field of rehabilitation. To address this, we have developed a prototype powered orthosis that utilizes non-invasive surface electromyography (EMG) signals from neck muscles, such as the sternocleidomastoid, for intuitive control. This EMG-driven system allows for the precise manipulation of the elbow joint, covering the full physiological range of motion. The prototype's design integrates an EMG signal processor with an orthosis action operator, creating a seamless interface between human intent and mechanical action. Healthy participants were able to use neck muscle contractions to control elbow rotation effectively, demonstrating the system's potential for real-world application. The scaled EMG envelope directly influences the orthosis's rotational actuator, ensuring responsive and accurate control. Through rigorous sensitivity analysis, we optimized the control algorithm by adjusting EMG window lengths, signal filtering, and thresholding parameters. This optimization process ensures that the system can adapt to individual user needs, providing personalized and efficient control. The real-time control achieved with this prototype marks a significant step forward in the development of biomedical rehabilitation devices. It not only offers a practical solution for those affected by elbow paresis but also lays the groundwork for future advancements in neuromechanical interfaces. Our ongoing research aims to refine this technology further, exploring the integration of signal processing algorithms to predict and adapt to user movements, thereby creating a more natural and intuitive user experience. The ultimate goal is to develop a fully functional orthosis that can be readily implemented in clinical settings, providing a non-invasive, effective solution for elbow rehabilitation.

Keywords: upper limb orthosis; electromyography signal; neck muscle activity

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Introduction

Recent advancements in mechatronic orthosis design have significantly enhanced the capabilities of upper limb rehabilitation and assistance devices. The promising direction is the development of passive orthosis for supportive and stabilizing functions [1] and the use of powered orthosis that can improve force generation and movement coordination [2]. This approach was demonstrated for the rehabilitation of stroke [3], traumatic injuries [4], multiple sclerosis [5], and cerebral palsy [6]. There are similarly efficacious demonstrations of powered orthosis in musculoskeletal disorders such as arthritis [7] and tendonitis [8]. The powered orthoses are becoming valuable tools to improve the quality of life and overall rehabilitation after neurological and movement disorders; however, their real-time operation in concert with the volitional commands of the user is challenging to achieve.

The two most common signals used for the volitional control of powered orthosis are electromyography (EMG) and inertial measurements [9]. The inertial measurements uses the position and acceleration data from the IMUs positioned on the forearm, upper arm and trunk to calculate the needed torque at the elbow to counteract the torque due to gravity. Results showed change on the muscle activity of four muscle groups when using the orthosis. The electromyography is used to interpret the user's motor intentions, enabling precise and real-time control of orthotic devices. This integration of technology and biology allows for a more natural and intuitive user experience, as the orthosis can respond dynamically to the user's muscle signals. The design of these orthotic devices incorporates a blend of mechanical components, sensors, and advanced algorithms to create a seamless interface between the user and the device. The use of EMG in this context is particularly revolutionary as it taps into the body's natural electrical signals generated during muscle contractions. By decoding these signals, the orthosis can execute movements that align closely with the user's intended actions with minimal delay.

The group of Vu Trieu Minh has developed an orthosis capable of holding and moving the elbow joint within a range of motion from 30° to 130° [6]. This orthosis incorporates a hinge with 17 holes, allowing for precise positioning, alongside mechanical stoppers and potentiometers for angle encoding. EMG signals from the biceps and triceps serve as control signals for proportional-integral-derivative (PID) regulation, enabling motor speed control and activation. Signal processing provided signal conditioning, scaling and further processing to detect movement onset through simple thresholding. Additionally, sophisticated control strategies, including adaptive linear quadratic Gaussian and Kalman filters, were employed to interpret EMG signals and regulate DC motors effectively.

Another approach focuses on a hybrid upper-limb orthosis device, utilizing a data-driven artificial neural network (ANN) classifier to interpret EMG signals for real-time control. This method has been applied to a 4-degree-of-freedom (DoF) power-assist exoskeleton, providing assistance in various upper-limb joint motions based on user intention [10] .

Study [11] investigates the development of orthosis devices for rehabilitation purposes, particularly targeting older adults in home settings. This design utilizes bandpass filtering and root mean square (RMS) signal processing techniques to enhance EMG signal quality and assess energy expenditure during physical exercises.

Other contributions include the integration of compliant actuators and control algorithms based on neuromusculoskeletal models, enabling user-safe orthosis operation [12]. Additionally, the research delves into the incorporation of additional sensors like inertial measurement units (IMUs) to estimate joint angles accurately, complementing EMG-based control with velocity and acceleration data [13].

Upon reviewing the existing literature on orthosis devices, we identified that neck muscle is the convenient way to take damaged muscle functionality. Additionally, we decided to implement a single-channel electrode configuration to turn on/off the orthosis to make movement instead of damaged muscle.

According to the information below, our goal is to develop a wearable open-system for orthotic control of elbow movement after peripheral nerve damage. Using off-the-shelf mechatronic devices and interfaces, we integrated a surface EMG recording capability from neck muscles and test 1 DoF control.

1 Materials and Methods

1.1 1-DoF upper limb orthosis design

We created a prototype of a simple modular 1 DoF orthosis with volitional interface through noninvasive recordings of neck muscle activity. The idea is that the orthosis is controlled by the neck muscle. Upon turning the head, the muscle construction is detected, and orthosis extends to a certain angle with a predefined speed profile. The reverse move of the orthosis is supposed to be implemented by a muscular force of the user: it is bent back by the person's hand.

For the proposed basic prototype, we implemented the following functionality: an extension from 0 to 90 degrees at a constant speed upon neck muscle contraction detected using single-channel EMG. We have developed a mechanical design, EMG measurement system, and a basic algorithm for contraction detection.

1.2 Block diagram of orthosis

In Figure 1, the following essential components of orthosis are presented:

- **Orthosis**: Positioned at the core of the system, the orthosis constitutes the physical structure responsible for supporting and regulating elbow movement. It serves as the interface between the user and the control mechanism;
- **ESP32 Microcontroller**: Serving as the central processing unit, the ESP32 orchestrates communication and coordination among the system's components. It implements bidirectional communication with the PC via TCP/IP, enabling data exchange essential for EMG signal processing and orthosis control. By receiving input from the EMG sensor and feedback from the angle decoder, the ESP32 governs the operation of the motor driver to ensure precise adjustments of the orthosis position;
- **Motor Driver (BTS7960)**: Acting as the bridge between the digital commands from the ESP32 and the physical movement of the orthosis, the motor driver regulates power to the orthosis motors. It interprets control signals to adjust motor speed and direction, facilitating smooth and accurate movement adjustments based on user requirements and feedback from the angle decoder. This regulation is achieved through the utilization of Pulse Width Modulation (PWM) signals from the ESP32;
- **Angle Decoder (AS5050A)**: The angle decoder serves as the sensory feedback mechanism, providing real-time information on the position of the orthosis. It accurately measures

the rotation angle of the orthosis hinge mechanism utilizing the Serial Peripheral Interface (SPI) protocol. The angle decoder relays crucial feedback to the ESP32, enabling precise control over the orthosis positioning;

- **PC (personal computer)**: As the interface for acquiring and processing EMG signals, the PC captures real-time muscle activity data. Through communication with the EMG sensor via UART (Universal Asynchronous Receiver-Transmitter) protocol, it gathers and processes EMG signals to extract relevant information regarding muscle activity and user intention. This processed data is then transmitted to the ESP32, guiding orthosis control decisions;

- **EMG Sensor (AD8232 and STM32F407)**: At the forefront of user interaction, the EMG sensor detects and measures electrical signals generated by the neck muscle contractions. Consisting of the AD8232 sensor and STM32F407 microcontroller, it captures muscle activity in real time and transfers analog values to the PC via UART for further processing.

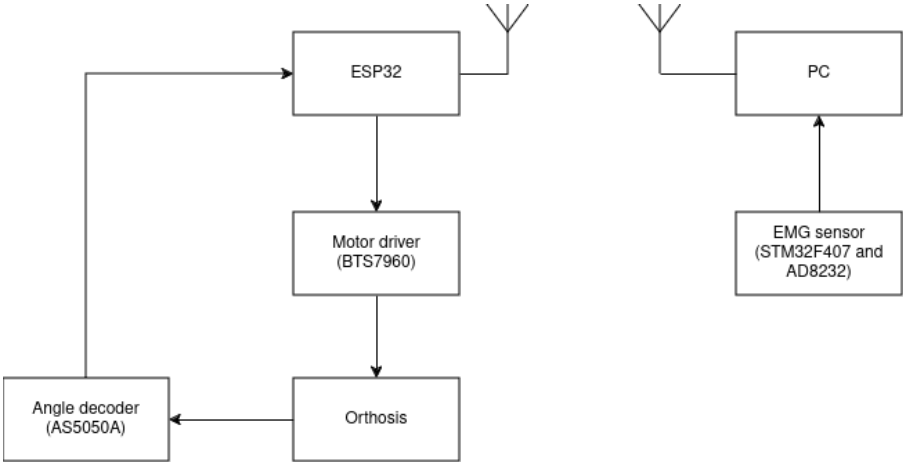


Fig. 1. Block diagram of orthosis control system with two parallel pathways to reduce interference. Right panel: The differential and referenced surface EMG signal is transmitted to the orthosis. Left panel: Control signals wirelessly (ESP32) provide reference signals for the orthosis motor driver (BTS7960). The high-powered DC motor achieves low-latency movement and provides positional feedback from angle sensor

1.3 Mechanical design of orthosis

Proposed design of the orthosis (Fig. 2) consists of two parts, one of which is fixed on the forearm and the other on the elbow. Each part of the orthosis is fixed with cuffs made of fabrics for medical devices. The two parts of the orthosis are connected to each other.

According to the technical requirements, the orthosis must be durable, reliable, and compact, and the geometric parameters of the orthosis, materials, and necessary technical characteristics were determined (see Table 1).

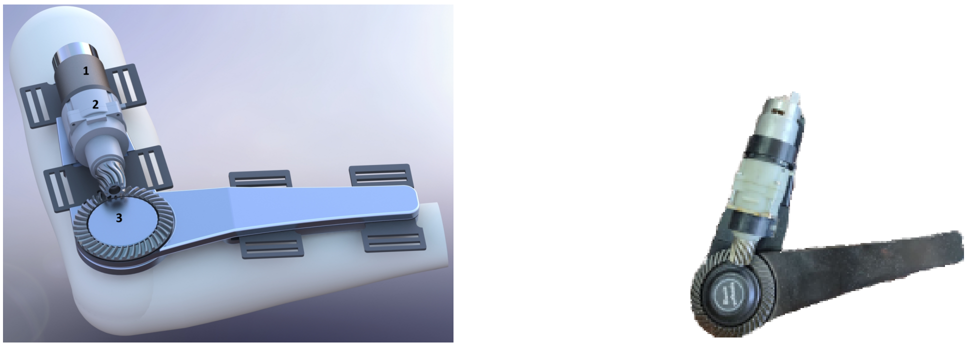
Table 1 Parameter set for orthosis setup

Necessary parameters	**Value**
Rotational speed, rpm	15
Torque, $N \cdot m$	17
Engine power, Watt	30
Mass of additional weight, kg	3,5

The required power of the electric motor and planetary gearbox was determined through rigorous testing. The orthosis was modeled to calculate the parts that could potentially be damaged during operation. In this work, we performed experiments separately without wearing the orthosis, orthosis was attached to a stand to observe its movements. This setup allowed us to calculate the distribution of stresses, deformations, displacements, etc., under various conditions, ensuring the mechanical integrity and safety of the device before any human trials.

1.4 EMG signal measurement for orthosis control

Sternocleidomastoid (SCM) neck muscle is responsible for the turn and nod of the head and is connected to the sternum, clavicle, and mastoid process of the temporal bone. The easy access to the activity of this muscle from the surface offers a ready source of control signal. Moreover, SCM activation may require less cognitive load to control ipsilateral elbow flexion compared to the alternatives sources, for example toggling switches with the opposite shoulder or pressing leg switches [14]. The EMG module, with electrodes placed on the SCM muscle area (Fig. 3) captures these signals at 1kHz sampling frequency. We use a single-channel EMG that is being recorded



(a) (b)

Fig. 2. Design of the orthosis: (a) Model of orthosis: 1 – motor, 2 – planetary gearbox, 3 – bevel gear; (b) Prototype of the orthosis

with three electrodes: a positive electrode (+), a negative electrode (-), and a reference electrode (Ref). Every second, a number of EMG samples equivalent to the **window size (Win)** parameter samples are transferred to the Data Queue for further analysis in the orthosis control system.

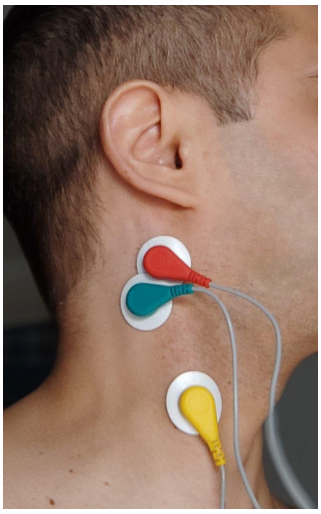


Fig. 3. Placement of EMG electrodes on sternocleidomastoid muscle. The differential recording was performed over the muscle (the differential recording was between red and green electrodes with yellow electrode as a reference)

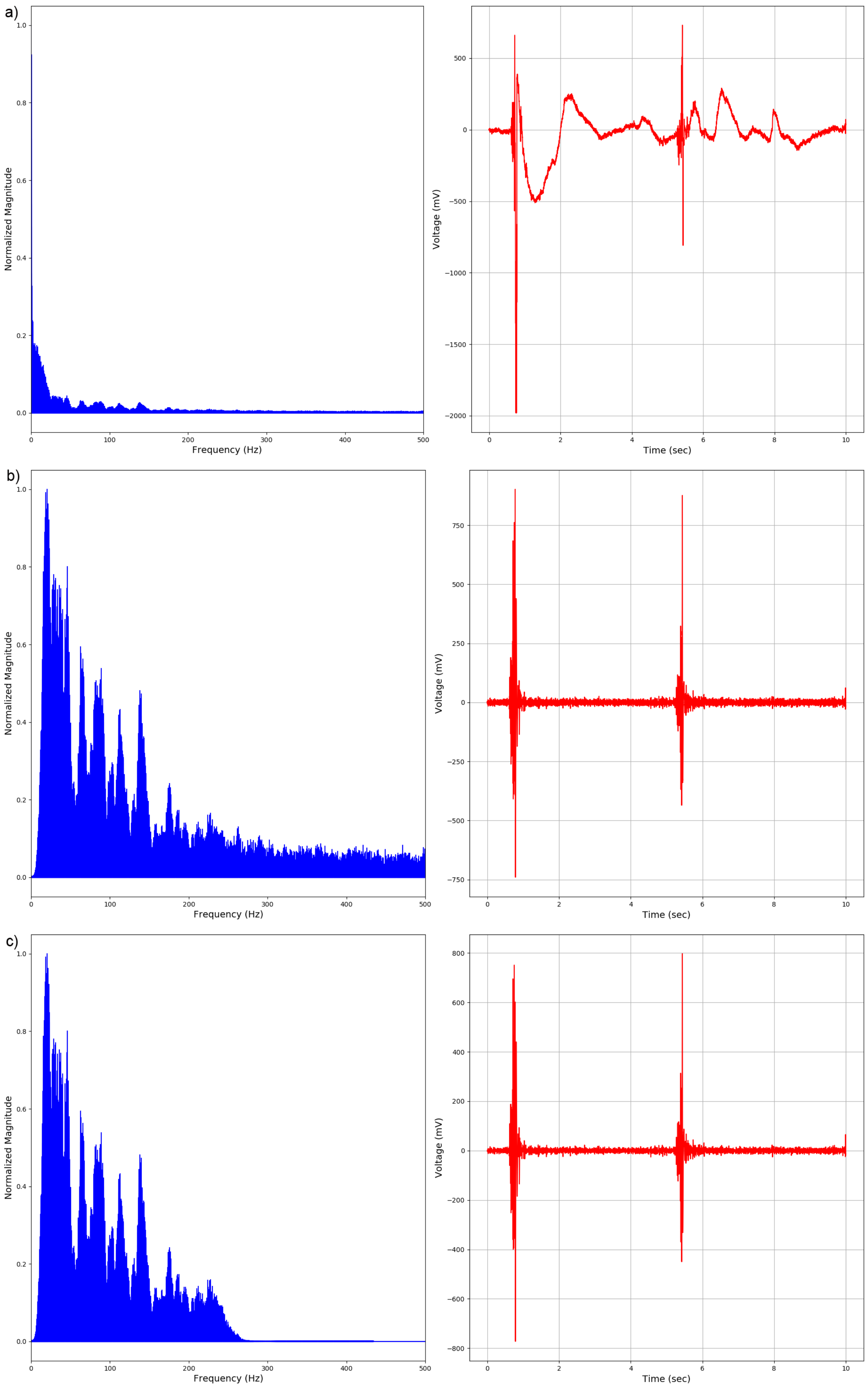
2 System architecture for orthosis control

2.1 EMG data collection and transfer

In the development of an orthotic device, we have established a mechanism for its activation and deactivation, governed by a personal computer. The system's architecture is built upon two concurrent threads. The Serial Thread is responsible for collecting data from the EMG sensor and placing it into the Data Queue. Then a newly recorded portion of EMG signal recordings is collected into a memory queue. If the queue length is more than predefined batch length then the oldest signals are removed to allocate space for new ones. The system also checks if the orthosis device is in a custom rest period (Re) which is the time period after a muscle contraction detected when the system is not supposed to detect the next neck movement. During the Re period we skip processing signals. When the system detects a muscle contraction, it sends a 'true' signal to the ESP32 microcontroller via TCP/IP protocol. This indicates that the user has performed a contraction. If no contraction is detected, a 'false' signal is sent, indicating no muscle activity. After each detection phase, the system resets by clearing the list of recordings, ready to analyze a new batch of EMG recordings.

2.2 EMG analysis method for neck muscle contraction detection

The contraction detection is performed for every second of the recorded EMG signal. Raw EMG passes through a high-pass filter with a cutoff frequency of 20 Hz. Subsequently, it undergoes processing through a 4th-order Butterworth low-pass filter with a 250 Hz cutoff frequency. Then filtered signal is rectified: converting all negative values of the filtered EMG signal to positive values. Post-rectification, the signal is further smoothed using a 4th-order Butterworth low-pass filter at a 6 Hz cutoff frequency [15]. All the steps of processing the EMG signal is depicted in Figure 4.


a)
Normalized Magnitude
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
Frequency (Hz)
Voltage (mV)
500
0
−500
−1000
−1500
−2000
0
2
4
6
8
10
Time (sec)
b)
Normalized Magnitude
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
Frequency (Hz)
Voltage (mV)
750
500
250
0
−250
−500
−750
0
2
4
6
8
10
Time (sec)
c)
Normalized Magnitude
1.0
0.8
0.6
0.4
0.2
0.0
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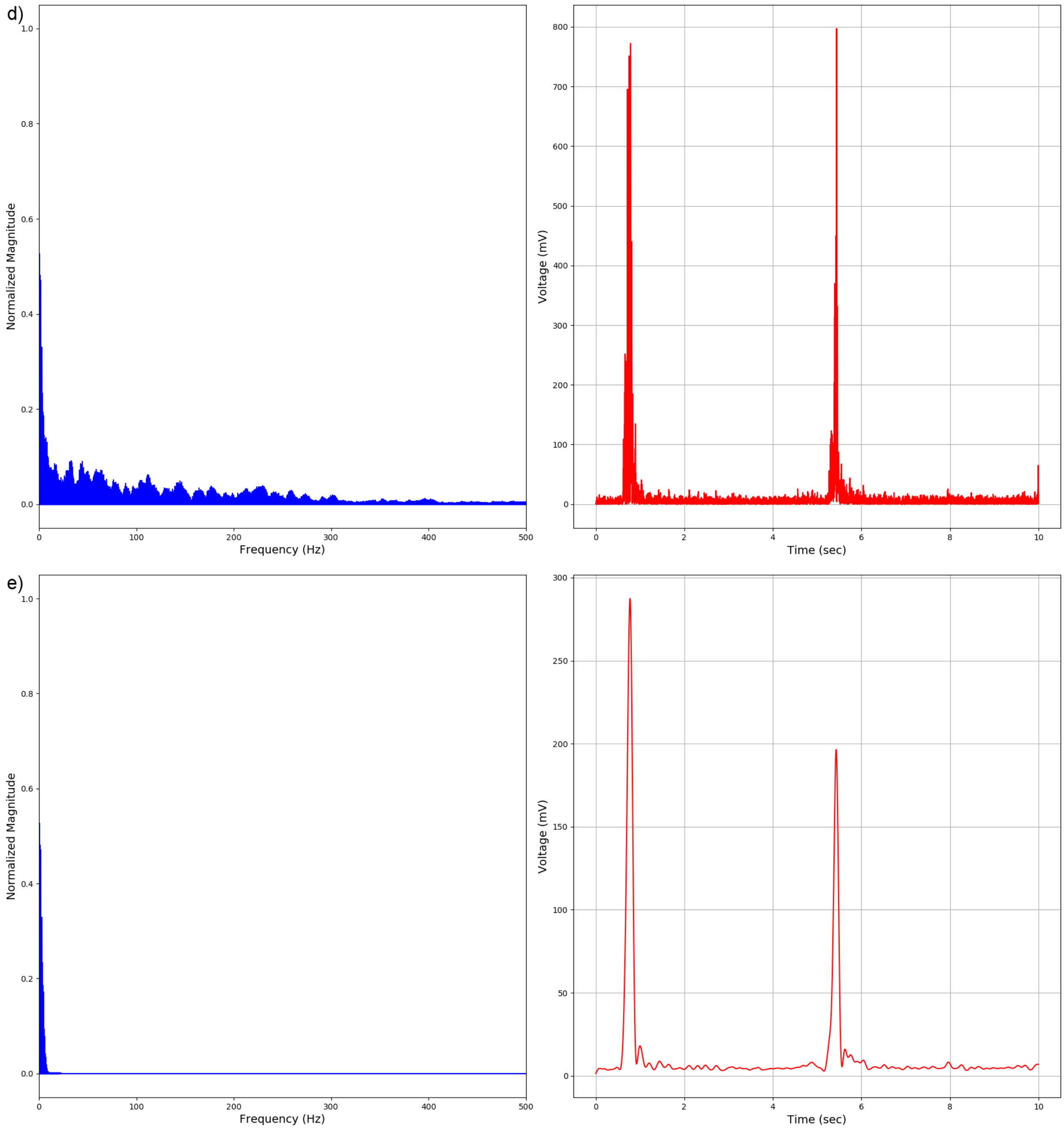


Fig. 4. EMG signal processing example: a) EMG signal before signal processing, b) Filtered signal with high-pass filter Fc=20Hz, c) Filtered high-pass signal with low-pass filter Fc=250Hz, d) EMG signal after rectification, e) EMG signal after rectification and low pass filtration Fc=6Hz

Next, the algorithm detects muscle contractions to determine the activation of the muscle. This detection process consists of the following steps:

- **Rejecting zero values**: EMG signal undergoes a preliminary screening to eliminate any values within a 10^{-4} neighborhood around zero. This is essential as the baseline of the EMG signal is typically non-zero, and zero values may indicate recording failures or signal artifacts. By discarding values around zero, we mitigate the risk of false positives during activation detection;
- **Checking if the amplitude meets the minimum threshold**: Following the rejection of zero values, the remaining EMG signal values are evaluated to ensure they surpass a predefined **minimum threshold (Th1)**. This threshold serves to distinguish meaningful muscle contractions from background noise or minor fluctuations. Only if the maximum EMG signal in the current window exceeds this threshold, the EMG is subject to further analysis for activation detecti-

on. If EMG is less than Th1, then the next time window is analyzed;

- **Calculating cumulative sums of two windows**: Then, EMG recording window is divided into two equal non-overlapping sub-windows, called left (from the beginning to the middle of the EMG segment) and right (from the middle to the end of the EMG segment). This segmentation allows for independent analysis of the signal parts. Next, we compute the cumulative sum for each sub-window and deducting the minimum value of the cumulative sum sequence within the sub-window to prioritize the rate of change in signal activity over absolute amplitude in the comparison of cumulative sums;
- **Comparing two cumulative sums**: In this step, we assess muscle contraction by comparing the last value in the cumulative sum sequence of the right sub-window with that of the left sub-window. If the right sub-window's cumulative sum exceeds the left's by a factor defined by a **custom relative threshold (Th2)**, it signifies a muscle contraction.

2.3 Experimental data collection software

For testing of the orthosis operation, specialized software for real-time collection and logging of EMG sensor data from neck muscles is developed. Also it allows capturing user interactions such as button presses, to support the analysis and evaluation of the orthosis performance.

During the data collection process, the user, equipped with an EMG sensor, performs neck rotations and presses the SPACE button in response to sound at regular intervals – every 5 or 10 seconds. The system records the EMG data and the button's state, logging a '1' for each press and a '0' when it is not pressed, all at a precise sampling rate of 1 kHz. For the illustration, see Fig. 5. This data is then queued and systematically written to a file. To ensure user control and convenience, the system includes an exit strategy, allowing the user to terminate the data collection at any time with the Ctrl+C key combination, thus completing the data logging process.

3 Metrics of algorithm performance

To estimate the EMG analysis performance, an algorithm is designed to evaluate the quality of neck muscle contraction detection. The algorithm operates on a temporal analysis window set around the time of button press events (red vertical line in Fig. 6), extending 0.15 seconds before and 0.3 seconds after the button is pressed. This window defines the expected time frame for a true muscle contraction event (Figure 6, orange pulse). The algorithm increments the true positive (TP) counter when a detected contraction (back vertical dashed line in Fig. 6) falls within this predefined range. Conversely, if the algorithm identifies a timeframe where the button indicates a contraction should be present, but no contraction is detected, it increments the false negative (FN) counter. Additionally, if a contraction is detected outside of the button press event - indicating no actual contraction occurred - the false positive (FP) counter is incremented [16]. These counters serve as the foundational metrics for calculating the following statistical measures:

Precision: This metric evaluates the proportion of true positives among all the positive predictions made by the model

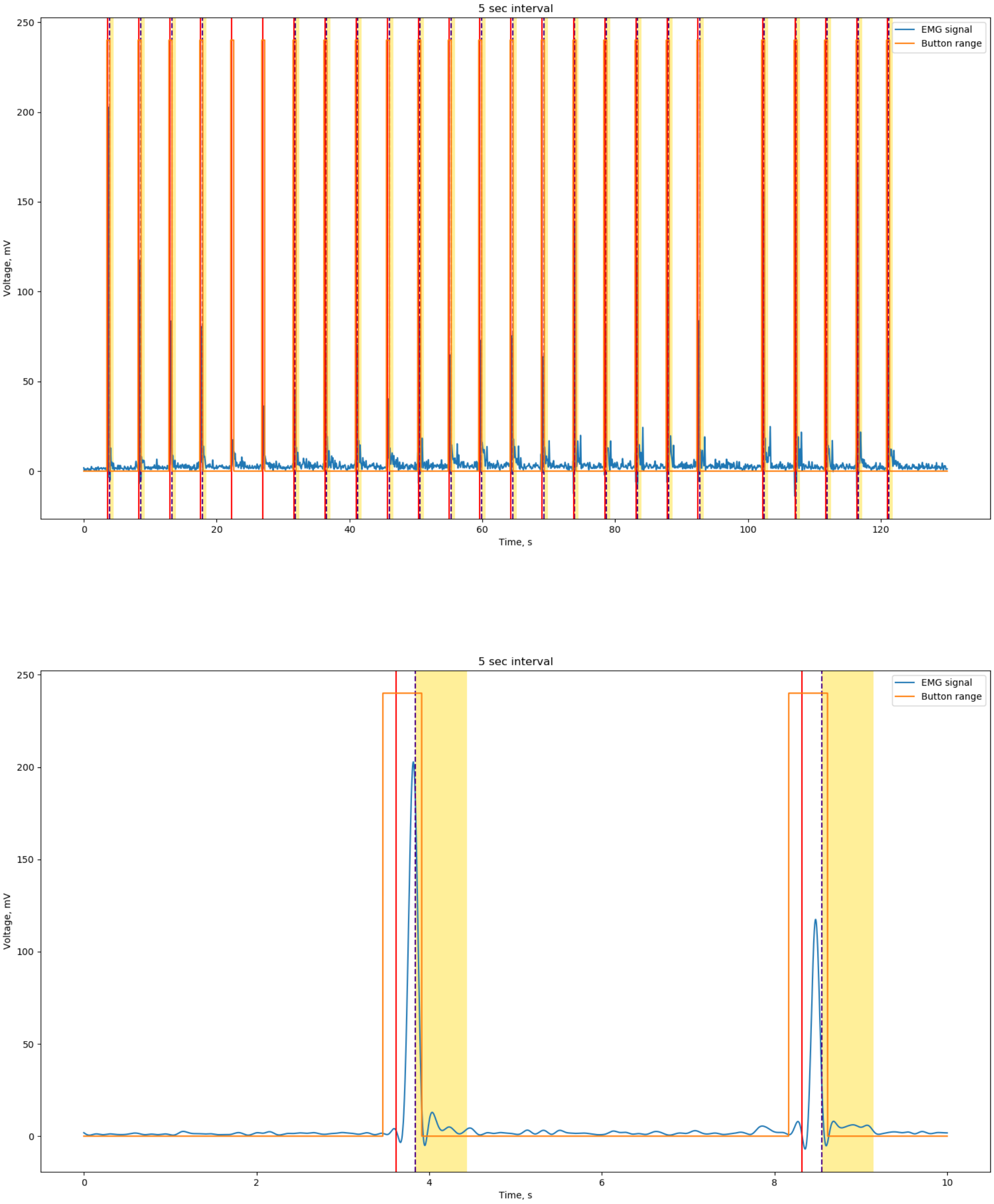
$$Precision = \frac{TP}{TP + FP};$$

Recall: Measures the proportion of actual positives that were correctly identified by the model

$$Recall = \frac{TP}{TP + FN};$$

F1-score: This is the harmonic mean of precision and recall, providing a balance between the two when they vary

$$F1\,score = \frac{2 \times Precision \times Recall}{Precision + Recall}.$$


5 sec interval
Voltage, mV
Time, s
EMG signal
Button range
250
200
150
100
50
0
0
20
40
60
80
100
120
5 sec interval
Voltage, mV
Time, s
EMG signal
Button range
250
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150
100
50
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0
2
4
6
8
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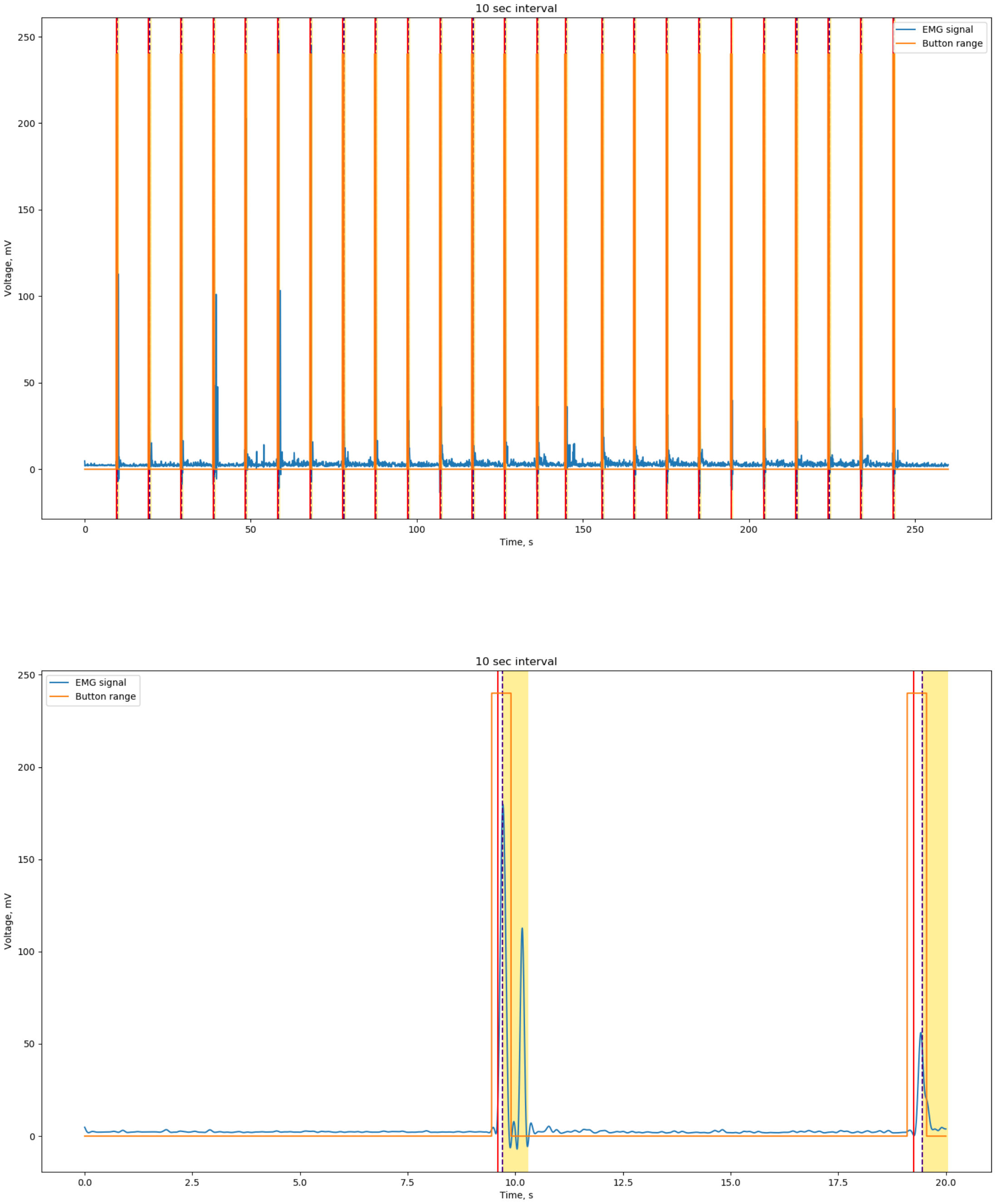
(a)



(b)

Fig. 5. Recorded EMG signal with button pressed events processed: (a) 5 sec interval; (b) 10 sec interval

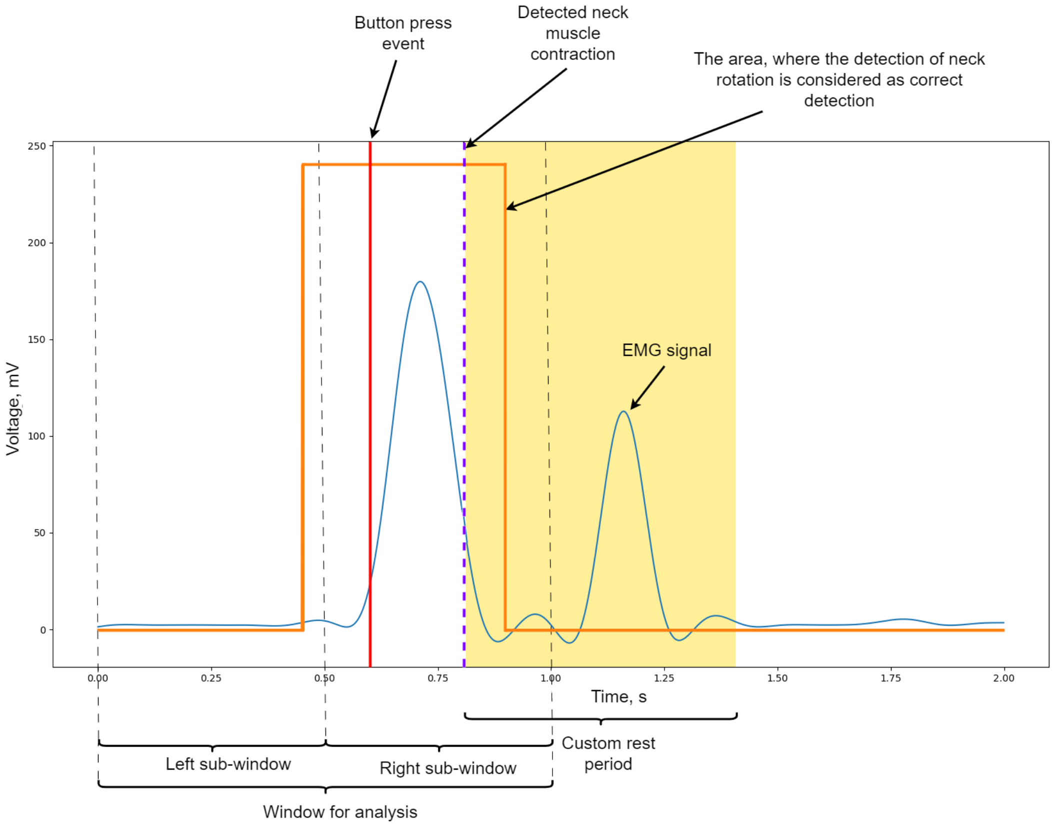


Fig. 6. Decoding button-press events from SCM EMG

4 Results

Upon the successful collection of 200 neck contractions – 100 with a 5-second interval and another 100 with a 10-second interval – the performance of the detection algorithm was evaluated. The algorithms were tested against the collected data to determine their effectiveness in accurately identifying muscle contractions.

First, we determined a minimum threshold (Th1) for EMG signal amplitudes to differentiate significant muscle contractions from background noise. Electrodes were placed on the non-muscular area of the back of the wrist, and signals were measured without movement. The average threshold value identified was 0.06 mV.

Second, we determined a custom rest period (Re) of 1 second based on the understanding that the user will not repeat head rotation before this duration.

Then we adjusted several parameters, including Window size (Win), to understand the optimal length of buffer and Custom relative threshold (Th2). These parameters were fine-tuned separately for the 5-second and 10-second intervals to optimize the algorithm's performance metrics such as accuracy, precision, recall, F1-score for each condition.

Then we built the 3D plots which illustrate the relationship between performance metrics with the Th2 and Win. The window size was varied from 0.4 to 2.0 s, and the custom relative threshold was adjusted from 0.5 to 10.0.

From 3D plots, we identified the maximum values for each metric which illustrates the Table 2. The primary metric that illustrates the efficacy of our classifier is the F1-score. For the 5-second interval, the maximum F1-score achieved was 0.6743, corresponding to classifier parameters of a window size of 1.11 and a custom relative threshold of 6.5897. For the 10-second interval, the maximum F1-score observed was 0.5834, with classifier parameters of a window size of 1.11 s and a custom relative threshold of 9.269. These findings result in the baseline for understanding the optimal settings for our classifier when detecting Sternocleidomastoid neck muscle contractions.

Table 2 The maximum values for each metric

Metric	**Value**	**Window size(s)**	**Custom Relative Threshold**
Max Precision 5s	0.6225	2.0	10
Max Recall 5s	0.832	1.2888	4.8846
Max F1-Score 5s	0.6743	1.1111	6.5897
Max Precision 10s	0.4777	0.9332	9.5128
Max Recall 10s	0.8442	0.9332	4.641
Max F1-Score 10s	0.5834	1.1111	9.269

Conclusion and further work

In this article, we developed the 1-DoF upper limb orthosis prototype that may be used in assistive technology for individuals with brachial plexus injuries. The integration of EMG signal processing with a responsive mechanical system allows for seamless and intuitive control of the elbow joint, offering a new degree of independence for users. Our testing and optimization of the system's algorithms have resulted in a solution that detects neck muscle contractions to facilitate movement.

We have proposed a muscle contraction detection algorithm based on calculating cumulative sums of two sub-windows and its comparison, which demonstrated acceptable accuracy and proved its efficiency in real-time processing EMG for orthosis control.

Using EMG data gathered via specialized software, we examined the correlation between performance metrics and modifiable parameters, including the custom relative threshold and window size. This analysis helped us to identify the optimal settings for these parameters, thereby enhancing the efficiency of the provided detection algorithm.

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Розробка мінімалістичного ортезу руки з електроприводом для лікування травм сплетіння плечового пояса

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Парез ліктьового суглоба, що часто виникає внаслідок травми плечового сплетіння, становить значну проблему в галузі реабілітації. Щоб вирішити цю проблему, ми розробили прототип ортеза з електроприводом, який використовує неінвазивні сигнали поверхневої електроміографії (ЕМГ) від м'язів шиї, наприклад стерноклеїдомастоїдний, для інтуїтивного управління. Ця система, керована ЕМГ, дозволяє точно маніпулювати ліктьовим суглобом, охоплюючи весь фізіологічний діапазон рухів.

Конструкція прототипу інтегрує процесор ЕМГ-сигналів з оператором управління ортезом, створюючи єдиний інтерфейс між намірами людини та механічною дією. Здорові учасники мали змогу використовувати скорочення м'язів шиї для ефективного контролю обертання ліктя, демонструючи таким чином можливості системи для застосування в реальних умовах. Масштабована огинаюча ЕМГ безпосередньо впливає на привід обертання ортеза, забезпечуючи чутливий і точний контроль. Завдяки ретельному аналізу чутливості ми оптимізували алгоритм керування, відрегулювавши довжину вікна ЕМГ, фільтрацію сигналу та параметри порогових значень. Завдяки цьому процесу оптимізації система може адаптуватися до індивідуальних потреб користувача, забезпечуючи персоналізований та ефективний контроль. Управління в режимі реального часу, досягнуте за допомогою цього прототипу, є вагомим кроком вперед у розвитку біомедичних реабілітаційних пристроїв. Він не тільки пропонує практичне рішення для людей з парезом ліктьового суглоба, але й закладає основу для майбутніх досягнень в області нейромеханічних інтерфейсів. Наші поточні дослідження спрямовані на подальше вдосконалення цієї технології, вивчаючи інтеграцію алгоритмів машинного навчання для прогнозування та адаптації до рухів користувача, тим самим створюючи більш природний та інтуїтивно зрозумілий користувацький досвід. Кінцевою метою є розробка повнофункціонального ортеза, який можна буде легко впровадити в клінічних умовах, забезпечуючи неінвазивне, ефективне рішення для реабілітації ліктя.

Ключові слова: ортез верхньої кінцівки; електроміографія; активність шийних м'язів