Revolutionizing Upper Limb Motor Control Restoration: A Novel EMG-Based Feedback System for Individuals with Neurological Diseases

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***Abstract*— This paper presents a detailed overview of the hardware and software components of a mechatronic exoskeleton system known as MANUTEX EMG. This system is specifically designed to assist individuals with movement disorders caused by neurological conditions. It focuses on aiding upper limb rehabilitation, with a particular emphasis on the distal extremities. In addition to providing movement assistance, the system facilitates the recording, storage, and analysis of patient progress data, which helps streamline monitoring efforts. By integrating linear motors for segment mobilization and EMG technology capable of detecting subtle muscle contractions, the system aims to improve motor control development. The final design underwent extensive testing with medical professionals at the Clinical Rehabilitation Hospital of Iasi to confirm its effectiveness and feasibility.**

Keywords—EMG, neuromuscular diseases, contraction detection, hybrid neuroprosthesis, hand rehabilitation devices.

I. INTRODUCTION

This article focuses on integrating electromyography (EMG) signals into upper limb rehabilitation devices, with a specific emphasis on understanding how muscle contractions are sustained through the activation of muscle spindles and central pathways.

EMG is a crucial tool in neuromuscular assessment, providing a non-invasive method to study both the normal and abnormal characteristics of muscles, allowing for a comprehensive exploration of muscle activity. Its versatility enables a broad spectrum of applications, such as analyzing gait abnormalities, different types of tremors, and acting as a sensor in rehabilitation programs involving various robotic devices.

Surface EMG evaluates the peripheral nervous system using monopolar or bipolar channels to study nerve network activity. The use of additional channels allows for the analysis of evoked activity, muscle-level action potentials, and the gradual development of muscle fatigue. By thoroughly examining motor units and nerve signals at the muscle level, a detailed understanding of the neuromuscular system's function can be achieved [1].

EMG, neuromuscular spindles, and spasticity are interconnected aspects of neuromuscular physiology and therapy. Understanding their significance in relation to movement disorders and therapeutic approaches is essential for medical practitioners. Recognizing these connections can assist in diagnosing issues, initiating treatment, and rehabilitating individuals with neuromuscular disorders.

EMG and muscle spindle activity are closely linked, contributing to proprioception and motor control. EMG functions as a "scanner," detecting electrical activity at the muscle level and highlighting muscle spindle stimulation during muscle contraction. Any anomalies detected by EMG may indicate physiological irregularities in the muscle spindle. To comprehend the functionality of a new system like the proposed MANUTEX EMG, it is vital to investigate muscle spindle function and factors influencing the development and persistence of spasticity.

Muscles contain muscle spindles with specific sensory receptors that play a critical role in conveying proprioceptive feedback to the central nervous system. Understanding these mechanisms can enhance our understanding of neuromuscular conditions and inform treatment strategies [2].

Muscle spindles are specialized mechanoreceptors with motor innervation via gamma motoneuron fibers, regulating stretch sensitivity. Proprioception is essential for understanding the spatial positioning and movements of body parts independent of visual cues. Proprioceptors detect changes in muscles, tendons, joints, and ligaments, primarily related to length, tension, and joint positioning. This information is then transmitted to the central nervous system to create a representation of body posture and movement.

Muscle spindles are especially abundant in areas requiring precise movement control, such as the arms. They contribute significantly to motor coordination and fine motor skills by providing detailed feedback on muscle length and tension [3, 4].

Muscle tone is a key factor in spasticity, representing the dynamic balance influenced by various control centers like the cortex, basal ganglia, cerebellum, reticular system, spinal cord, and muscle spindles. Essentially, muscle tone refers to the level of tension in a muscle unit when it is at rest [5].

EMG discerns the actively contracting segment of the muscle while unable to detect its passive counterpart. The passive portion encompasses a viscoelastic component comprising viscosity, elasticity, osmotic pressure, connective tissue, sarcomeres linked to non-contractile proteins, elongation of contractile filaments, and supplementary elements [6].

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Muscle tone is regulated by mechanisms operating at both spinal and supraspinal levels. Understanding the mechanics of muscle contraction requires elucidating the complex interaction between muscle spindles and the spinal cord. Within each muscle spindle are intrafusal muscle fibers, which are categorized into two types. Nuclear bag fibers contain a central region with multiple nuclei surrounded by contractile structures resembling a bag. These fibers respond to changes in muscle length and the speed of contraction [7, 8].

The nuclear bag fibers are divided into two types: type 1 (b1) and type 2 (b2) intrafusal fibers. Nuclear chain fibers are elongated muscle fibers with nuclei arranged in a linear fashion. They respond to changes in muscle length, detect static alterations, and contribute to maintaining tone and posture.

Muscle spindles contain distinct nerve endings: nuclear bag fibers type b1 have annulospiral fibers type Ia, while type b2 fibers have both type Ia and type II nerve endings. At their ends, they have contractile zones innervated by gamma and beta neurons.

Similarly, nuclear chain fibers have flower spray endings of both type Ia and II, with contractile regions at their ends also innervated by gamma and beta motoneurons [9, 10].

Motor commands are transmitted to alpha motor fibers, which in turn activate gamma motor fibers simultaneously. This alpha-gamma co-activation leads to the contraction of both extrafusal (ordinary muscle fibers responsible for generating force) and intrafusal fibers (muscle fibers within muscle spindles that detect muscle length changes). This coordinated contraction helps regulate muscle tone and sensitivity to changes in muscle length during movement [11, 12].

Several interneuronal components are critical in the stretch reflex and contribute to maintaining muscle tone. Muscle tone is predominantly influenced by recurrent inhibition via Renshaw cells, reciprocal Ia inhibition from antagonist muscles, non-reciprocal Ib inhibition by Golgi tendon organs, and presynaptic inhibition.

Moreover, supraspinal structures exert influence on muscle tone through three inhibitory pathways (corticospinal tract, corticoreticular tract, dorsal reticulospinal tract) and two stimulating pathways (vestibulospinal tract and medial reticulospinal tract). Among these pathways, the dorsal spinoreticular tract plays a particularly significant role in regulating muscle tone [13].

The cerebellum is closely connected with the reticular formation, allowing it to modulate the activity of gamma motor neurons through the reticular formation. This modulation can result in either a decrease or increase in muscle tone [14].

An initial version known as MANUTEX has been developed to integrate functional electrical stimulation (FES) and mechatronic components in an upper limb rehabilitation system designed for stroke patients [15].

The core principle of the algorithm is to achieve a balanced and coordinated control between FES and the mechatronic exoskeleton, leveraging input from the healthy hand through a sensory glove to assist stroke patients in restoring mobility in the affected hand during therapy sessions. MANUTEX includes software responsible for converting and transmitting commands to both FES and mechatronic components, and clinical testing has demonstrated significant improvements in motor recovery among patients.

The earlier version of the MANUTEX device did not incorporate any EMG signal input. The control algorithm is engineered to deliver rapid response times and reliable operation, featuring a user-friendly interface tailored for therapists. MANUTEX represents an innovative approach to rehabilitating the affected hand in stroke patients and paves the way for potential CE certification in the future [16, 17].

The innovative MANUTEX EMG device is engineered to detect the intention to move the hand through continuous monitoring of the EMG signal. When a specific threshold is reached, the mechatronic glove will initiate the hand's opening motion before returning it to its default position. The EMG value is simultaneously displayed on a graphical user interface and saved in an Excel file for further analysis.

A newly developed software interface has been implemented to manage the hardware components, utilizing a control algorithm tailored for this application.

II. HYBRID EXOSKELETON AND EMG CONTROL METHOD

A. System Overview

The novel device MANUTEX EMG comprises two primary components. The first element is the mechatronic glove, which facilitates the mechanical movement of the affected hand. The second component consists of an EMG reading module responsible for measuring the signal and transmitting it to the microcontroller.

The analog signal undergoes conversion to digital format and is continuously compared to a preset threshold. Once the threshold is reached, the microcontroller ceases the analog-to-digital conversion monitoring and proceeds to issue commands to the linear actuators using Pulse Width Modulation (PWM) technique.

Throughout this comparison process, the microcontroller transmits the EMG value to the graphical user interface via USB. A graphical representation is displayed in real time, and simultaneously, the value is logged into an Excel file for subsequent analysis.

The block diagram of the MANUTEX EMG device is presented in Fig. 1 and enlists the main blocks.

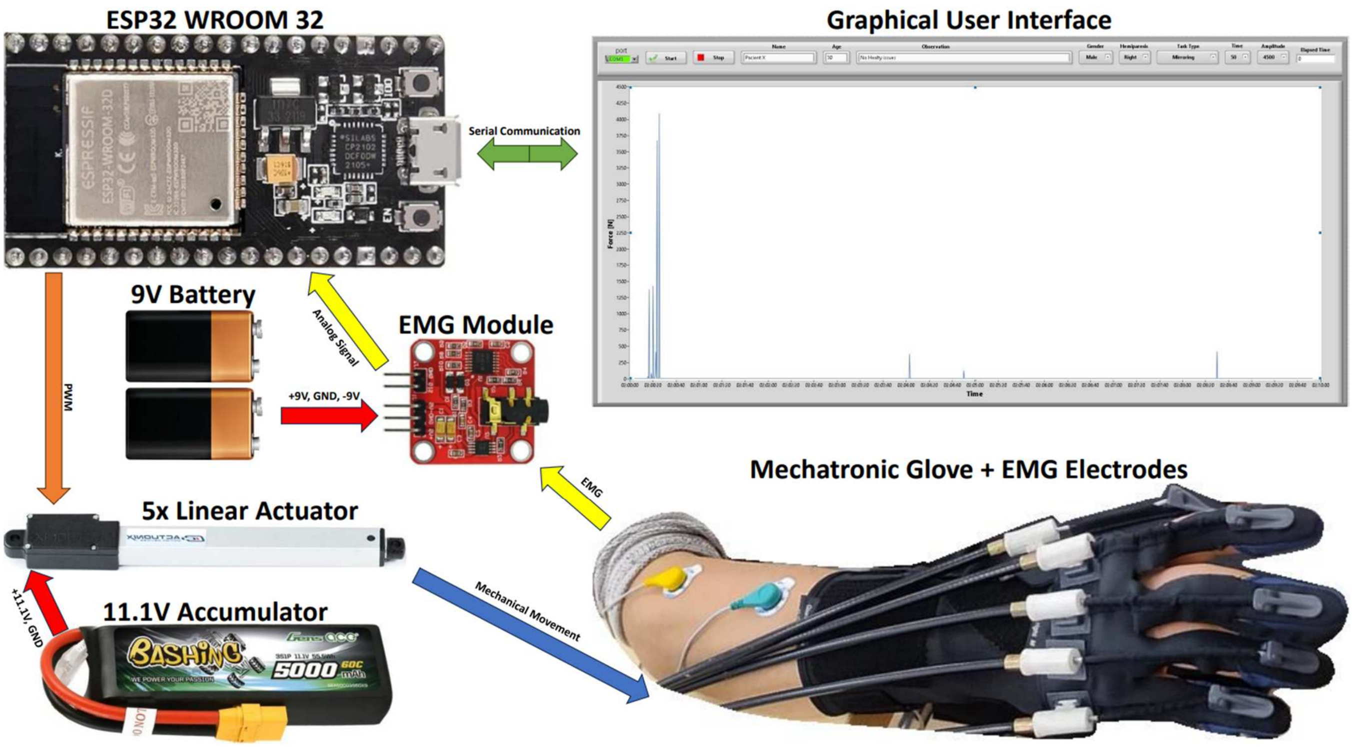

Fig. 1. The MANUTEX EMG block diagram.

The mechanical movement is supported by five micro-linear actuators (L12-100-210-12-I; Actuonix: Stroke length 100mm; Force: 100 N (at mid-stroke); Speed: 12 mm/s (no load); Input Voltage: 12 VDC; Current: around 100 mA to 200 mA depending on load and operation conditions; Gear Ratio: 210:1; Control: Internal limit switches and position feedback (potentiometer); Duty Cycle: 20% (2 seconds on, 8 seconds off)), one actuator for each finger. These actuators are connected to the mechatronic glove through iron wires as shown in Fig. 1. The software realizes the initialization, calibration, and the controlling of each actuator independently by using PWM signals (1kHz with variable duty cycle) generated by an ESP32 WROOM32 board.

The EMG signal is monitored using an H124SG module, which undergoes several stages of signal processing. These stages include difference amplification, a high-pass filter, a precision full-wave rectifier, a low-pass filter, an adjustable amplifier, and finally, a difference amplifier connected to an offset selector. At its output, an analog signal is generated that is directly proportional to the EMG value.

The core of the MANUTEX EMG system is the ESP32 WROOM 32 module which is a low-cost system on a chip microcontroller that integrates WI-FI and dual-mode Bluetooth.

The linear actuators are powered by an Accumulator LiPo Gens Ace Bashing 5000mAh 11.1V 3S1P 60C XT90, initially employed as a DC power source. However, this led to significant noise interference on the EMG signal. The ESP module is directly powered by the laptop via USB, receiving 5V. The next phase involves establishing wireless communication between the laptop and the actuators, with the power supply to be facilitated by the 11.1V accumulator.

The Graphical User Interface (GUI) is created by using a LabVIEW program where the EMG value sent by ESP32 module are displayed on a graph and at the same time this data will be saved in a customed Excel file. Fig. 2 represents the graphical user interface:

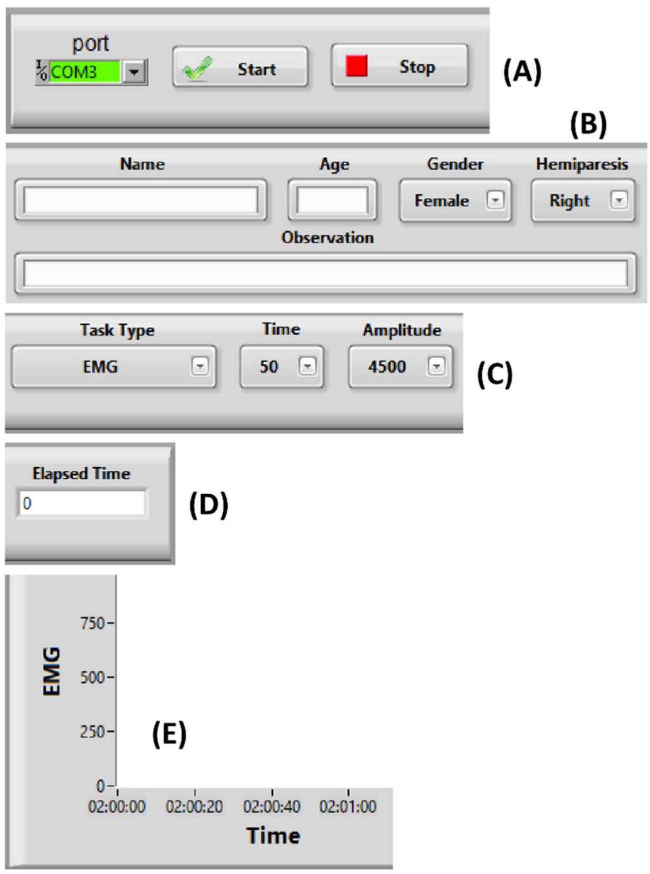

Fig. 2. The designed Graphical User Interface.

In the graphical user interface (GUI) initial step, users select the port to which MANUTEX EMG is connected. Patient information, including age, gender, and relevant disease-related data (ensuring compliance with GDPR regulations), is entered into the GUI to monitor daily outcomes and generate comprehensive reports. Prior to commencing the test, users set the threshold value and task parameters (Figure 2, section C). Throughout the task, the EMG values are graphically represented in real time (Fig. 2).

Throughout the task, the patient attempts to move their affected hand, during which the EMG signal is monitored. Upon reaching the selected threshold, the mechatronic glove will maintain the hand's movement for an open-close cycle. To assess improvements over time, the graphical user interface records EMG values in an Excel file for subsequent analysis.

The schematic and the layout were created using Easy EDA platform and the printed board circuit was realized by using a CNC model WEGSTR.

The software component of the MANUTEX EMG System implemented on the ESP32 development board is engineered to execute several critical stages in its workflow, essential for the rehabilitation process using a hand exoskeleton. This detailed process is pivotal in leveraging electromyography signals for the actuation of the mechatronic exoskeleton, facilitating physical therapy for patients with impaired hand mobility (Fig.3).

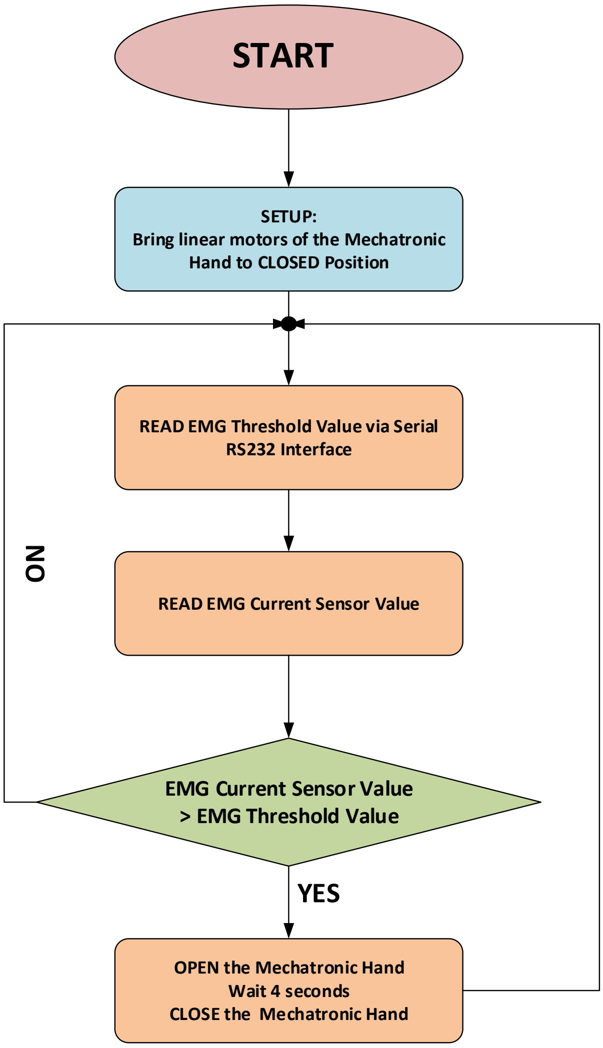

Fig. 3. The MANUTEX EMG main control & data conversion software component logical diagram.

Here's an overview of the system's operational workflow:

B. *Initial Setup Routine*

Upon powering the device, an initial setup routine commences that lasts approximately seven seconds. During this period, the primary objective is to position the hand exoskeleton into a fully closed state. This positioning is critical for ensuring that the exoskeleton can be easily mounted onto a patient's hand. The focus on a fully closed state implies a preparatory step for a fit that accommodates a wide range of hand sizes and shapes, optimizing the device for immediate therapeutic use.

C. *Continuous Loop Operation*

After the initial setup, the device enters into a continuous operational loop, which forms the core of its functionality. This loop involves several key steps:

- EMG Threshold Retrieval: Initially, the firmware retrieves the EMG Threshold value from an external application. This retrieval is facilitated through the RS232 Serial interface, a standard for serial communication that ensures reliable data transfer between the device and the external application. The EMG Threshold value is a crucial parameter that determines the sensitivity of the system to EMG signals, essentially setting a benchmark for what is considered a significant muscle activity.

- EMG Current Sensor Value Reading: Following the threshold retrieval, the system acquires the current sensor reading from the EMG sensors attached to the patient's hand. This reading reflects the real-time muscle activity in the patient's hand, providing a quantitative measure of the electrical signals generated by muscle movements.

D. *Condition-Based Actuation*

The core logic of the system is then applied, where if the EMG Current Sensor Value exceeds the pre-defined EMG Threshold Value, it triggers a specific sequence of actions:

- The triggered sequence aims at initiating a full extension followed by a full flexion of the Mechatronic Exoskeleton. This dual action mimics the natural movement of the hand, stretching and contracting the muscles, thereby aiding in rehabilitation.

- There is a brief pause of about four seconds between the extension and flexion phases. This interlude is designed to give the patient time to adjust to the movement, minimizing discomfort and ensuring a gradual adaptation to the exercise.

E. *Repetitive Iteration*

The described process is not a one-off occurrence. Each time the EMG Current Sensor Value exceeds the EMG Threshold Value, the sequence of extension, pause, and flexion is reiterated. This repetitive nature of the exercise ensures continuous engagement of the affected hand muscles, promoting recovery through repeated practice and muscle memory development.

This operational workflow demonstrates the fusion of biomedical engineering principles with cutting-edge mechatronics and sensor technology, providing a refined method for hand rehabilitation. Utilizing EMG signals to activate the exoskeleton ensures therapy responsiveness to the patient's muscle activities, thereby augmenting the naturalness and efficacy of the rehabilitation process.

III. Results

Initially, the main objective was to validate the new features of the MANUTEX EMG system by conducting tests on healthy participants in a laboratory setting. The verification process involved two main steps. First, the integrity of the EMG signal and its reliable communication with the graphical user interface were confirmed. However, during this phase, noise was detected in the EMG signal. This issue prompted an investigation, which ultimately led to the replacement of the 12V DC power source with an 11.1V accumulator to minimize interference and improve signal quality.

In the subsequent step (Step 2), the entire MANUTEX EMG system underwent thorough testing. This included adjusting the threshold across its entire range and verifying the movement of the linear actuators (Fig. 4). Multiple software adjustments were implemented based on the outcomes of these tests, with a particular focus on refining the timing sequence to optimize system performance.

The graphical user interface (GUI) of the MANUTEX EMG system allows for the storage of all data in Excel files, enabling convenient analysis. This interface facilitates real-time detection of muscle contractions by the EMG module, identification of any artifacts (such as noise), and observation of relaxation periods in tested subjects (indicating a lack of muscle electrical activity) (Fig. 5). These data are crucial for quantifying recovery outcomes and establishing an environment that supports the demonstration of improvements in motor control during MANUTEX EMG sessions.

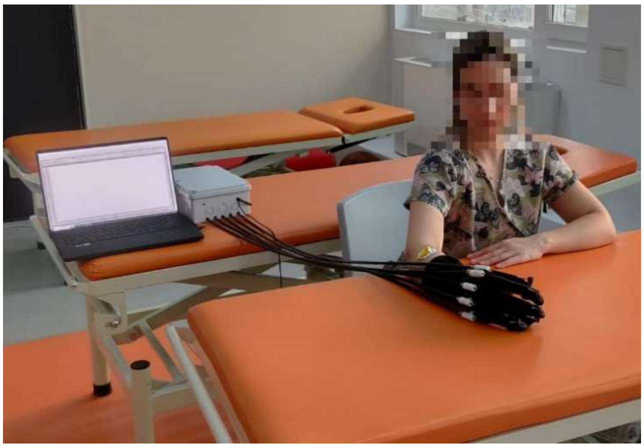

Fig. 4. The MANUTEX EMG device was tested on medical personnel.

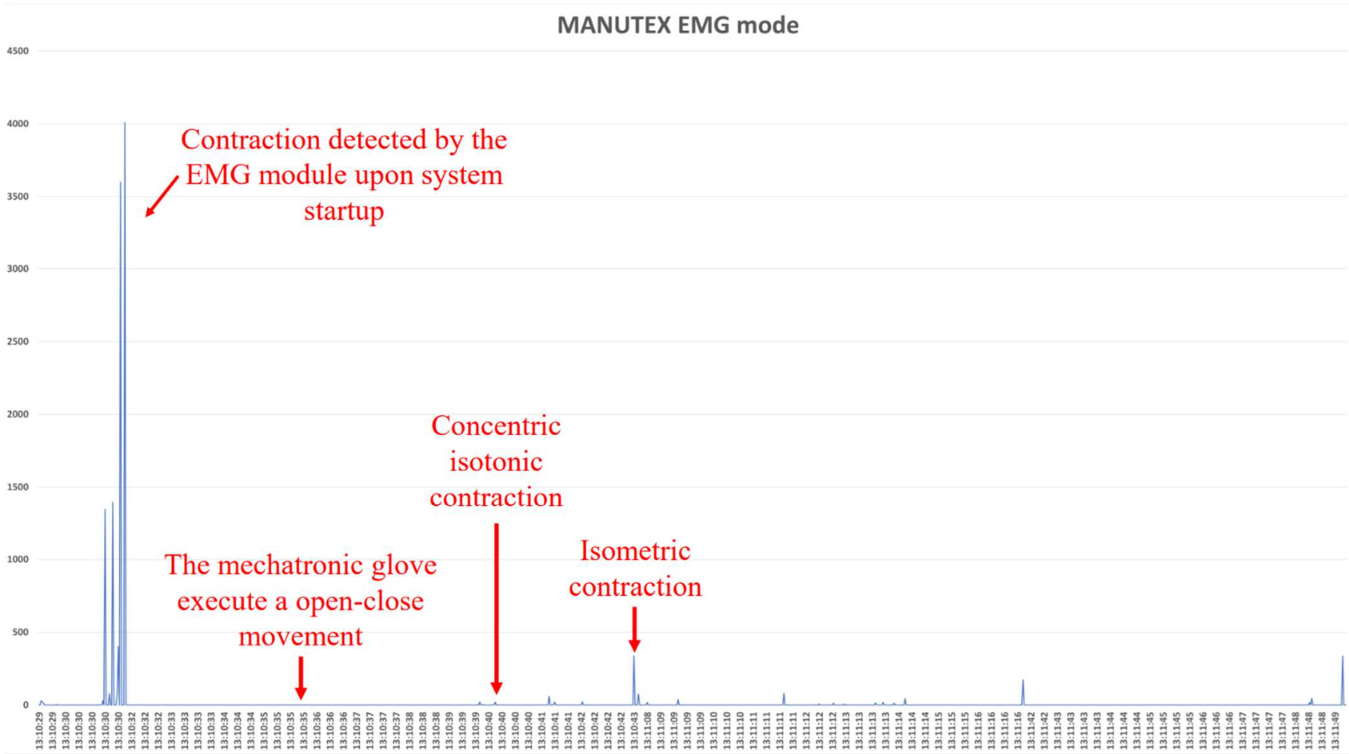

Fig. 5. The MANUTEX EMG mode

In the second phase of the study, the MANUTEX EMG System was strategically placed in a dedicated neuromotor rehabilitation chamber within the Clinical Rehabilitation Hospital of Iasi, ensuring convenient access for the evaluated groups. Here, we conducted testing on two groups of participants: a group of healthy volunteers and a group of patients.

Before recruiting the group of healthy volunteers, they were provided with comprehensive information about the technology and its operation. They were then asked to consent to participate in the study. The same protocol was followed for patients undergoing testing with the equipment.

After developing the mechatronic rehabilitation device, an evaluation was carried out to assess its effectiveness in achieving targeted movements. A diverse group of healthy volunteers, including medical professionals from various departments, was assembled. Their feedback was crucial in refining the system's functionality and usability.

The next phase of this project involves establishing a partnership with the Rehabilitation Hospital of Iasi

(Neurology Clinic), where stroke patients will undergo testing under the supervision of neurologists and physiotherapists. This collaboration aims to evaluate the device's performance and its impact on rehabilitation outcomes for stroke patients.

IV. DISCUSSION

Stroke is a severe neurological condition characterized by impaired motor function, often resulting in significant disability and reduced quality of life. Restoring motor function in the upper limb is crucial in stroke therapy, as it directly impacts an individual's ability to perform daily tasks and regain independence.

Recent technological advancements have led to the development of innovative rehabilitation devices aimed at improving motor function outcomes for stroke survivors. The implementation of the MANUTEX EMG system represents a significant advancement in restoring upper limb motor function in individuals with post-stroke spasticity. This system is specifically tailored to address the unique needs of stroke survivors, focusing on rehabilitating the distal segments of the upper limb extremities.

Stroke survivors commonly experience challenges in upper limb motor function, including muscle weakness, spasticity, and impaired coordination. Traditional rehabilitation methods often rely on therapist-led interventions, which may not always offer specialized and intensive training tailored to each patient's specific needs. The MANUTEX EMG device overcomes these limitations by providing a comprehensive approach to stroke therapy.

The device offers prompt feedback and precise control over therapeutic interventions by integrating mechanical engineering and EMG technology. Stroke survivors can engage in repetitive exercises aimed at improving muscle strength, coordination, and motor function. Additionally, the system's ability to collect, store, and analyze patient progress data enables doctors to accurately track rehabilitation outcomes and adjust treatment plans accordingly.

This personalized approach to stroke rehabilitation has the potential to enhance recovery outcomes and improve the overall quality of life for stroke survivors. Numerous research studies have explored the effectiveness of rehabilitation devices utilizing EMG technology in improving upper limb motor function post-stroke. While study designs and methodologies may vary, the overarching goal remains consistent: to enhance upper limb motor function and improve outcomes for individuals recovering from stroke.

Diogo Farinha et al. conducted a study presenting the development of a prototype Assistive Robotic Hand Orthosis (ARHO) designed to assist individuals with hand impairments in grasping objects. However, the prototype currently falls short of achieving intended features in terms of weight, wearability, and utility.

One significant limitation is the system's inability to provide somatosensation to the palm and fingers, which is crucial for receiving feedback during tasks that involve object manipulation. This limitation could lead to usability challenges, including increased spasticity in the user's hand and wrist, lack of durability, and restricted range of motion.

The current prototype is based on a standardized design, which may not fully accommodate the specific needs and circumstances of individual users. These challenges highlight the importance of ongoing development and refinement to enhance the functionality and usability of assistive technologies like the ARHO for individuals with hand impairments [18].

In a study by Cassie Meeker and colleagues, a test was conducted on a Hand Orthosis designed to provide Functional Grasp Assistance following a stroke. This work represents significant progress in developing wearable orthoses controlled by electromyography signals. However, the study's reliance on a small sample size of only 4 stroke survivors limits the broader significance of the findings.

The training procedure for using the orthosis is complex, involving communication and physical engagement, which may restrict its practicality and long-term applicability beyond clinical settings. Additionally, the study acknowledges technical challenges such as signal delays caused by filtering and issues related to spasticity, highlighting the need for further improvements in the control system to enhance usability and effectiveness.

Overall, while the study demonstrates promising advancements in functional grasp assistance for stroke survivors, addressing these challenges will be crucial for optimizing the technology's performance and adoption in real-world settings [19].

Kaichi Fukano et al. introduced and evaluated a model utilizing deep learning for myoelectric prosthetic hands, aiming to classify hand gestures using surface Electromyography signals with Convolutional Neural Networks (CNNs). The study's goal was to accurately and swiftly convert EMG signals into hand gestures, ultimately improving the performance and usability of myoelectric prosthetic devices in everyday life.

The researchers aimed to meet the crucial requirement of precisely mapping muscle EMG signals to finger motions, essential for efficient myoelectric prosthetic hand function. They sought to develop a highly accurate model capable of identifying a wide range of hand motions using deep learning techniques, specifically CNNs.

However, the study faced various obstacles and constraints. These included inconsistencies in user performance, the need for extensive training to enhance data quality, and potential challenges in reliably identifying intricate motions. Addressing these challenges is essential for the successful implementation of deep learning models in myoelectric prosthetic devices, ensuring robust and reliable performance in real-world scenarios [20].

Wei Rong et al. developed and evaluated an alternative rehabilitation technique for hand dysfunction following a stroke by integrating an EMG-controlled robotic hand device with neuromuscular electrical stimulation (NMES). The study aimed to assess the combined impact of NMES and robotic assistance on enhancing hand function in stroke survivors.

Specifically, the study sought to statistically measure the training benefits of the NMES-robot system and explore its potential to improve motor recovery in people with chronic stroke. However, the study faced significant constraints and challenges. These included the need for larger sample sizes and extended follow-up evaluations to establish long-term effectiveness.

Additionally, there were concerns about potential over-reliance on technology, complexity, and cost implications of the intervention, as well as the possibility of negative effects and varying responses among patients. The study highlighted the urgent need for further research to refine the intervention, address these constraints, and maximize positive outcomes for stroke rehabilitation using NMES and robotic assistance. Ongoing research efforts will be essential to optimize the integration of these technologies into stroke rehabilitation protocols [21].

Over the years, various devices designed to improve spasticity have been developed and examined. However, these devices often have complex structures, significant weight and dimensions, and additional costs associated with their acquisition and maintenance. Furthermore, many of these devices are primarily usable within clinical environments, limiting their accessibility and ease of use for patients with severe spasticity in everyday life.

Due to these factors, it remains challenging to view these devices as straightforward options for improving the quality of life for patients with severe spasticity. The limitations related to device complexity, practicality, and accessibility underscore the ongoing need for innovative solutions that are more user-friendly, cost-effective, and suitable for use outside clinical settings to truly enhance the daily lives of individuals affected by severe spasticity [22, 23, 24, 25].

Further research on MANUTEX is needed to fully explore its unique benefits and versatility. One notable advantage is its lightweight design, which enables easy transportation and use in any environment. This feature is particularly valuable for patients with spasticity, as it allows them to integrate the device into their recovery program without interference. Additionally, the portability of MANUTEX compensates for the shortage of therapists, potentially accelerating patient recovery by providing consistent and accessible rehabilitation sessions at any time of day.

The versatility of MANUTEX extends beyond clinical settings, offering flexibility and convenience for patients to use the device in various environments, including home-based rehabilitation. This adaptability can enhance patient engagement and compliance with therapy, ultimately contributing to improved recovery outcomes.

While MANUTEX presents promising benefits, ongoing research is essential to validate its effectiveness, optimize its usability, and explore its potential impact on rehabilitation outcomes for individuals with spasticity and other neurological conditions. Continued development and evaluation will further elucidate the role of MANUTEX in enhancing patient recovery and quality of life.

V. Conclusions

Figure 6 illustrates how the MANUTEX EMG system represents a significant advancement in rehabilitation technology for individuals with movement disorders stemming from neurological conditions, with a specific focus on upper limb rehabilitation, particularly targeting the distal aspect.

By integrating mechatronic elements with EMG technology, this system offers a comprehensive approach to enhancing the rehabilitation process while enabling continuous monitoring of patients' progress over time. The use of linear motors for segment mobilization and EMG technology for muscle contraction detection facilitates precise motor control development, which is essential for successful rehabilitation outcomes.

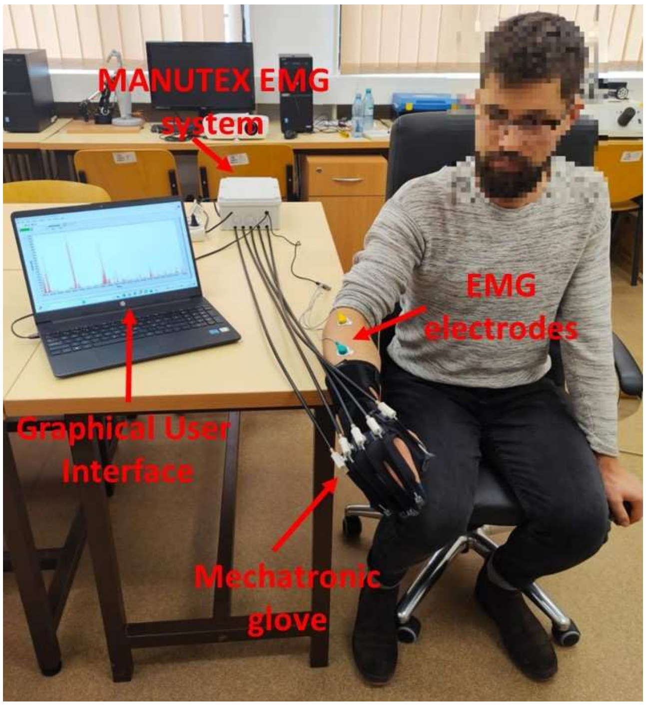

Fig. 6. The novel MANUTEX EMG system used in laboratory tests.

Although awaiting clinical validation at the Clinical Rehabilitation Hospital of Iasi, the system shows promising potential in improving motor recovery for patients. The introduction of a novel feature to detect and assist hand movement in stroke patients enhances the system's versatility and suitability for clinical environments.

Future partnerships with rehabilitation hospitals aim to validate and refine the system for practical deployment, highlighting its capacity to significantly influence the rehabilitation outcomes of individuals with neurological disorders. While clinical validation is pending, this device holds promising possibilities for improving motor recovery and rehabilitation outcomes for patients with post-stroke spasticity.

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