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PRELIMINARY TESTS OF A NEW HYBRID FES-EXOSKELETON ASSISTING DEVICE FOR THE UPPER LIMB IN STROKE PATIENTS

BY

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Abstract. Neuroplasticity is the functional recovery after a nerve injury which consists in reorganization of nervous tissue based on the formation of new connections between neurons and synthesis of new cells. This paper proposes new devices which open new ways of functional recovery of the upper limb in disabled people, whom functions were partially or totally lost by CVA (cerebro-vascular accident), head injuries, spinal injuries, etc. The proposed systems combine anthropometric dimensioned mechanical structures of exoskeleton types and functional electrical stimulation technology, with modular and reconfigurable design, fact that makes them adaptable for either the right or left upper limb. The role of robotics rehabilitation devices is essentially in any health care system by reducing the rehabilitation treatment costs.

Key words: stroke; assistive robotics; functional textiles; functional electrical stimulation; disabled people.

1. Introduction

Nowadays, the vascular brain injury becomes one of the biggest threats to the population at a global scale. The lethality due to stroke reached a value of 11% for women and 8.4% for men. Prospective studies show that this condition

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increases year by year, both by incidence and prevalence. Studies made by experts within the World Health Organization (WHO) estimate that in 2030 stroke will become the first cause of mortality. Currently, in Romania there are about 300 new brain strokes per 100,000 inhabitants, compared to a European average of 200 strokes and about 900,000 citizens have suffered one or two strokes. In the last few years, the age at which stroke occurs in Romania began to fall, many new cases being diagnosed under 40 years. According to WHO statistics, Romania ranks first in terms of mortality and major disability (Popescu *et al.*, 2009).

In 2008 - 2010, a group of researches (Neagoe *et al*, 2010) have studied the incidence of stroke in Romania. The study was conducted on a total of 468,635 patients, 212,714 men (45.4%) and 255,921 (54.6%) women diagnosed with stroke. The data was collected from hospitals during 2008-2010. They concluded that stroke will become, by 2030, the leading cause of death in the world, at around eight million deaths annually. Globally, between 2-4% of health services are related to stroke and exceed 4% in developed areas (Strong *et al.*, 2007). Another study from 1990 shows that Britain spent 7.6 billion pounds, Australia 1.3 billion Australian dollars and the United States of America 40.9 billion US dollars, which results that they spent about 100$ per capita per year (Rosamond *et al.*, 2008). Specialist doctors argue that among the persons suffering a stroke, a third die in the first year after the accident, a third remain permanently disabled, and the rest are recovered.

The research aimed at people with motor disabilities resulted in chair-bed transfer aids, walking neuroprotheses or stretching-grip control function of the upper limb (Taylor *et al.*, 2000, Fuhr *et al.*, 2001). Various studies have investigated the effects of functional electrical stimulation (FES) on motor qualities of the upper limb after stroke and emphasized its effectiveness (Wang *et al.*, 2002, Church *et al.*, 2006, Linn *et al.*, 1999). Assisting robotics allows patients to perform repeated movements in a well-controlled manner, while the FES-based activation of the muscles helps the brain to learn again the movements involved in daily activities (Serea *et al.*, 2015). The specialists have named this phenomenon as neuroplasticity. Neuroplasticity is the property of functional recovery after a nerve injury as a result of taking over by other nerve structures and the reorganization of nervous tissue that is based on the formation of new connections between neurons and/or synthesis of new cells.

Nowadays different research institutes are investigating the possibility to produce textile electro-conductive electrodes (Zieba *et al.*, 2011, Li *et al.*, 2010, Curteza *et al.*, 2014). A textile composite electrode has been proposed in (Zieba *et al.*, 2011), it has been sewed on the textile product and its resistivity has been investigated. A FES system that helps stroke people to walk better and therefore improving their quality of life, or helping them in rehabilitation of the upper limb requires reliable electrodes for stimulation. Actual used electrodes are disposable ones, with conductive gel which has to be replaced quite often. During our researches we proved that knitted electrodes might be a viable solution with benefits in terms of ease of positioning and reliability.

This paper presents a hybrid FES-exoskeleton system designed for the rehabilitation process of the upper limbs in stroke patients. Beside the new balanced control of an exoskeleton and FES-based muscles contraction, the electrical stimulation might be provided by means of knitted electrodes integrated within functional textiles. Overall, the proposed system has the premises to enhance the motor capabilities of the patient's upper limbs with neuromotor disabilities.

2. The System Description

For generating electrical stimulus needed to induce muscle contraction and thus functional movements of the upper limbs, an 8-channel neurostimulator (MOTIOSTIM8 produced by KRAUTH + TIMERMANN GmbH) has been programmed and controlled via MATLAB&Simulink environment. The exoskeleton joints were actuated by means of four DC motors with gear reducer. Based on the control strategy, two Sabertooth controllers are provided with pulse width modulated signals in order to drive the motors of the exoskeleton.

The main predefined movements are shoulder flexion-extension, abduction-adduction, medial rotation of the shoulder and forearm flexion extension. The first part of the system is presented in Fig. 1. The second part consists of an actuated glove and will be presented later on.

Fig. 1 – The left arm exoskeleton.

The position of each joint of the exoskeleton is read by linear potentiometers connected to each drive shafts. Their recorded signals are fed into the ports of a Basic Atom 28Pro microcontroller and converted analog to digital with a resolution of 10 bits. The general scheme of the control structure for the FES-exoskeleton system is shown in Fig. 2.

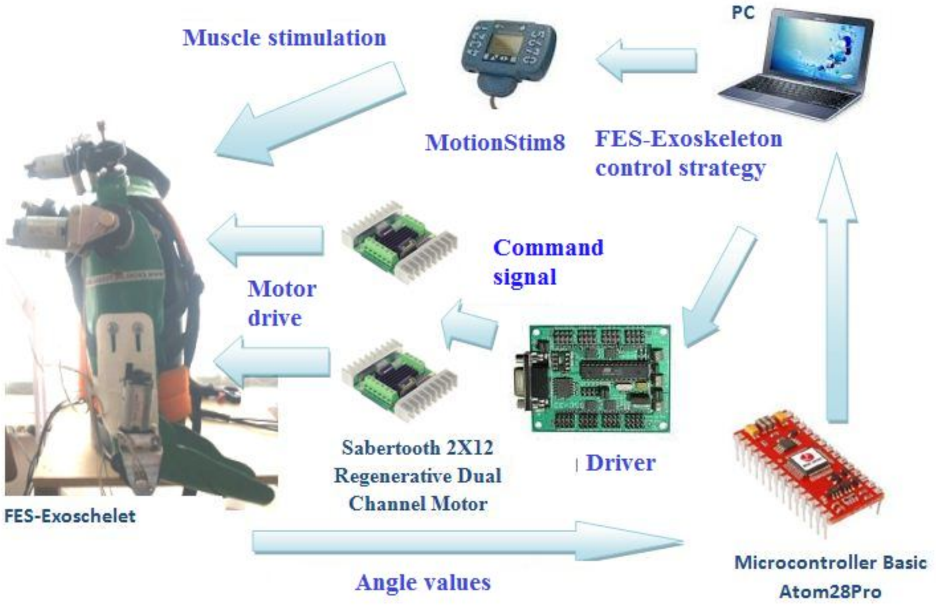

Fig. 2 – The general scheme of the control structure for FES-exoskeleton.

For the medial rotation and elbow flexion-extension we used one H-bridge Sabertooth controller which can provide a nominal current of 10A per channel, reaching the peak value at 15 A. The control for each channel of the controllers is via modulated pulse width at a frequency of 50 Hz. Sabertooth Regenerative Motor Controller Dual Channel 2 × 25 is used for the shoulder flexion-extension and abduction-adduction, which has 25A rated current at a voltage of 18 V and a peak current of 50 A. The Sabertooth device is controlled with a standard R/C signal with pulse widths varying between 1.0ms to 2ms, at a frequency of 50 Hz. The switching frequency of the Sabertooth dual H-bridge controller is 35 kHz. The supply voltage can be obtained from either a voltage source or from the Ni-Cd or Li-Po batteries. For a pulse width of 1,500 µs the motor shaft is locked. Increasing the pulse width leads to clockwise rotation of the motor shaft. The value corresponding to the maximum speed is 2,500 µs. Reversing motion is done by decreasing the pulse width to less than 1,500 µs. The 500 µs value corresponds to a maximum speed counterclockwise. The control signals for the two regulators are provided by SSC-32 controller, in turn controlled by the coordinator computer via a RS232 serial port.

The second part of the system is a hand rehabilitation device which also has a hybrid drive by means of electrical drives and electrical stimulus applied over forehand and hand. Fig. 3 is a schematic diagram of the hardware system detailing the connection between the glove exoskeleton and sensors, and electrical stimulation.

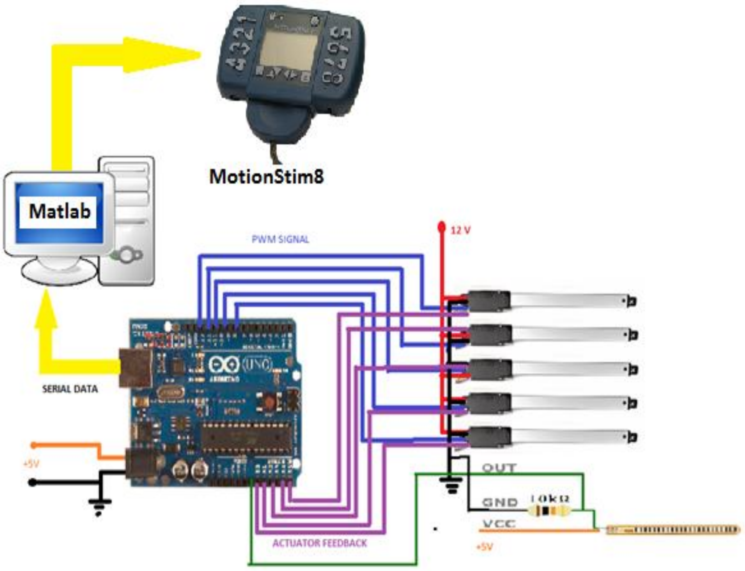

Fig. 3 – The hardware structure of the robotic glove system.

The glove is operated by linear actuators. This prototype was designed to perform two types of exercises:

a) the first one, a predefined one, consists in detecting the hand movement intention of the patient, using a bending sensor mounted on one of his fingers in order to perform the flexion and extension of the hand,

b) the second aims to copy the healthy hand movements and to drive the glove movements, the glove being mounted on the impaired hand.

The self-made leather glove has been fitted in the metal clamp for fixing the tendons. One end of the tendon is fixed to the clip of the fingertip and the other on the actuator arm. The artificial tendons are fixed to the platform that supports the engine. The glove is fixed on each finger into two points with a velcro as shown below in Fig. 4.

Fig. 4 – Velcro fixing.

The signals from the glove sensors are acquired and processed by the Arduino Uno microcontroller and transmitted through the RS232 serial interface and interpreted in the Matlab programming language as a percentage. The electric stimulus intensity is directly proportional to the percentage shown in Matlab. At 100% a maximum stimulation is provided and decreases proportionately for the flexion. The maximum stimulation parameters are deduced within the testing phase for each user.

To achieve the second type of exercise on the right hand glove, the mounted sensors will detect the finger movement, see Fig. 5.

Fig. 5 – Glove with sensors fo copying the healthy hand movements.

In order to complete the FES-Exoskeleton system a functional textile with knitted electrodes has been used (Fig. 6).

Fig. 6 – Knitted electrodes within a functional textile to produce the required functional electrical stimulation.

The process relied on the use of electro conductive yarns that can be bought on the market which have been knitted (like socks parts) to form isles positioned in such a way that one textile electrode covers the proximal forearm near the elbow and another the second covers the distal forearm near the wrist.

3. Laboratory Results

The system has been tested on two subjects and there have been replicated the flexion and extension of the arm and forearm. The control strategy was developed and implemented for the combined operation of the exoskeleton and functional electrical stimulation. Fig. 7 shows images from the experiment that was conducted for assisted control.

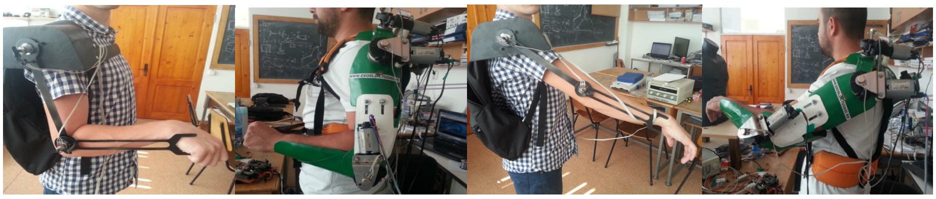

Fig. 7 – Images from the experimental assisted control.

The assisted control was realized with proportional integral derivative action controllers (PID). The PID controllers have continuous action and provide superior control performance in stationary and transient regime.

PID controllers have three adjustable parameters KR, TI, TD. The answer of the system given by the PID parameters, with Kr = 1.3, TI = 0.55 and TD = 0.7 is shown in Fig. 8 for a sudden change of angle and in Fig. 9 for a normal operation.

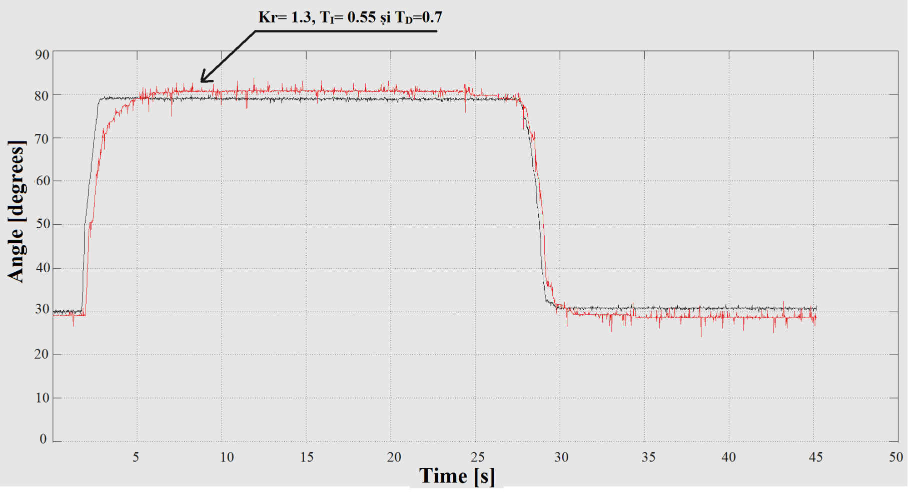

Fig. 8 – PID response for a sudden change of the reference angle.

The PID-controlled implemented system has been tested on another healthy subject. During the test there have been replicated the flexion and extension of the arm and forearm with functional electrical stimulation together with electrical drive. The correspondence stimulation channel - stimulated is: Ch1 – Triceps, Ch2 – Biceps, Ch3 – Anterior deltoid, Ch4 – Posterior deltoid. The stimulation frequency used was 50 Hz. Before starting the experiment the subject was tested in order to establish the maximum stimulation parameters for each muscle group. The results for the assisted control training are shown in Fig. 10.

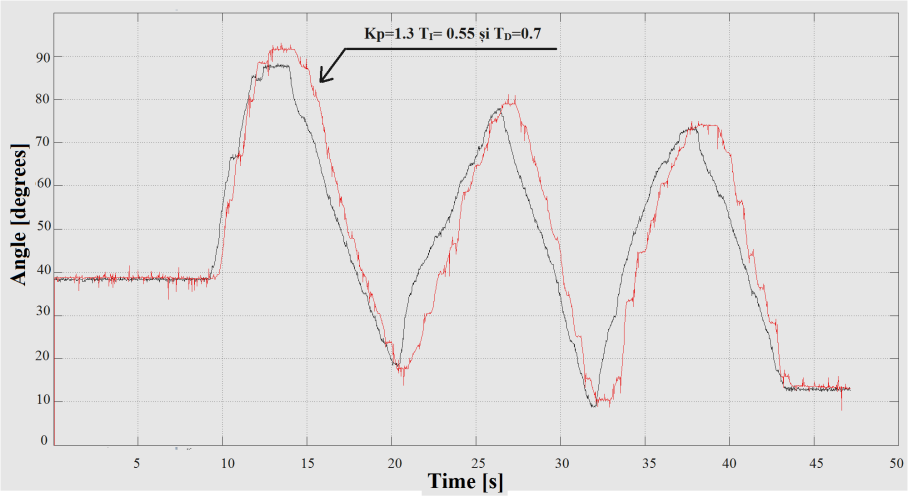

Fig. 9 – PID controller response in normal operating conditions.

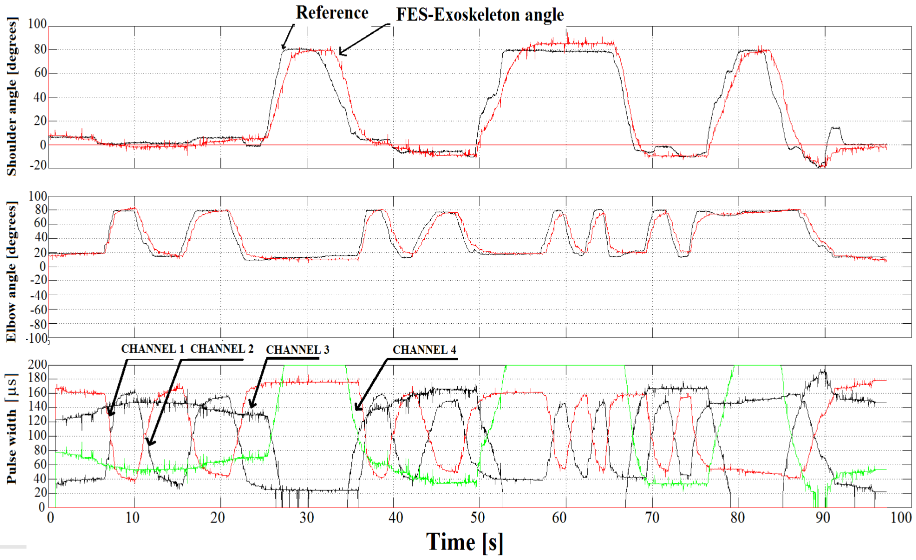

Fig. 10 – Assisted control.

The electrical stimulation increases proportionally with extension of the hand that has motor deficit. When the hand is in a position of total flexion, the signal provided by the flex sensor (green) has a value of 100%, and if it is in full extension has a value of 0%. The circled signals numbered 1-3 represents the movement intentions of the subject, see Fig. 11. The system performs the extension and flexion movement in a timeframe of 5-6 s and after performing it the system waits again to detect the subject's intention to move the hand and to execute a new set of exercises (see Fig. 11).

While testing the device on one healthy patient the values of electric stimulus for channel 1 was PW = 265 µs and a current of 9 mA and for channel 2, 305 µs and a current of 10 mA. Higher electric stimulus (channel 2) is used to stimulate the extensor muscles of the hand and the lower value are used for finger extensor muscles (channel 1), see Fig. 11.

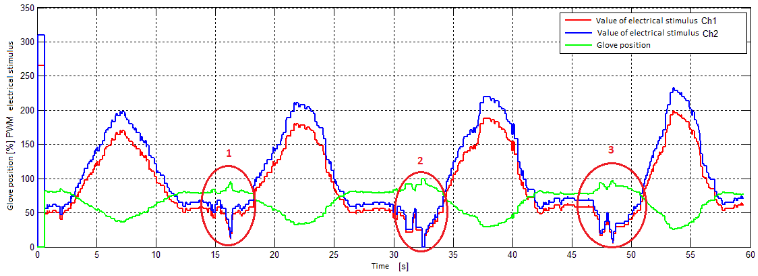

Fig. 11 – The signals corresponding to the default exercise with intention detection.

The subject performed the predefined exercise for flexion/extension of the hand without detection of movement, see Fig. 12. The time required to perform the exercise of flexion/extension depends on how much time the electrical stimulation remains active. For the first two exercises, when the hand was in a position of extension, the electrical stimulation was maintained for 5 s at its maximum value, and for the last exercise we maintained 7 s the electrical stimulation at its maximum value.

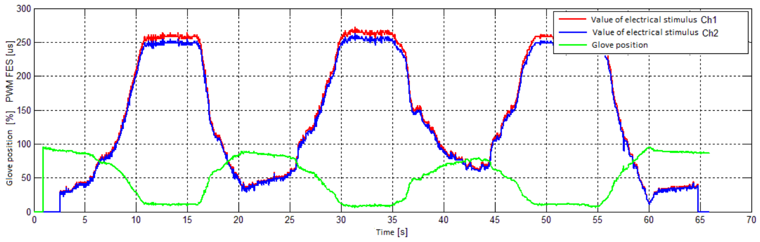

Fig. 12 – Signals corresponding to the default exercise without detecting the intention.

Within the second exercise (copying the healthy hand movement) two tests have been done. The first one aims to determine the time of flexion/extension of the hand with motor deficit, where his/her healthy hand is closed/open in one second Fig. 13. During the second test the healthy hand and the motor impaired hand were moved in the same time. In that case, the electrical stimulus is kept at a constant maximum value for five seconds while performing each extension movement.

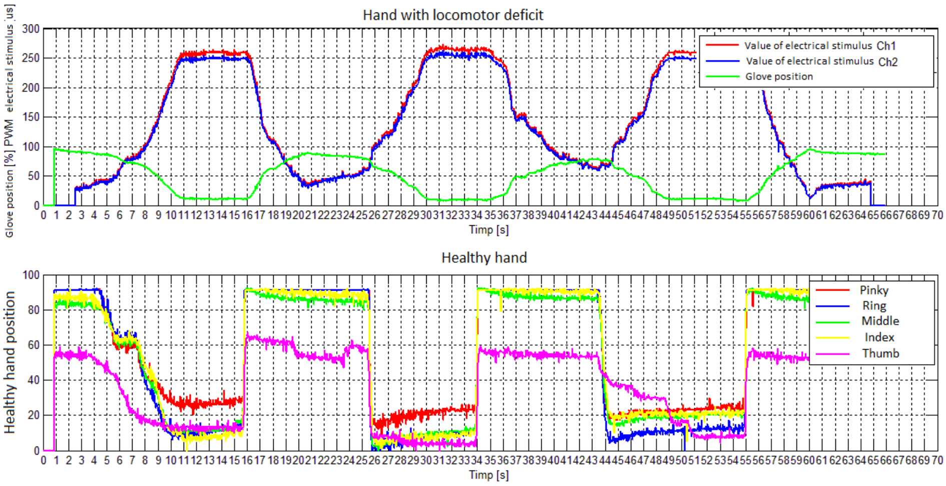

Fig. 13 – Signals corresponding to the exercise of copying the healthy hand movement.

From the grafic above, we can observe that the healthy hand opens/closes in 1 s, while the impaired hand does the same movement in 4 s. The glove with sensors can be used as a test instrument in order to determine the degree of mobility and dexterity of impaired hand.

4. Conclusions

The present paper presented a new hybrid FES-exoskeleton prototype aiming to rehabilitate the impaired upper limb in stroke patients. It integrates also novel knitted electrodes embedded within functional textiles.

The proposed system differentiates from the existing systems by using a combined control, balancing between electrical drives control of an exoskeleton and functional electrical stimulation. The main part of the upper limb rehabilitation system, consists of a mechanical exoskeleton type structure, anthropometrically sized, aiming to ensure basic anatomic movements (shoulder flexion-extension, shoulder abduction-adduction, shoulder medial rotation and forearm flexion-extension) together with functional electrical stimulation. It has a modular, reconfigurable structure, thus adaptable for either the right or the left sides. The system has been successfully tested on two subjects.

The glove system, which completes the first part, has also an anthropometrical design and its movement is based on artificial tendons as well as electrical stimulation over the forearm and hand. It can assure the hand's flexion and extension. This second part is conceived as an exoskeleton that supports the hand activities, using a control architecture for dexterity, grip and handling. In other words, it is a medical device acting in parallel with the hand in order to compensate a lost function. This system meets three characteristics for grip strength control: the system supports gripping forces proportional to the human hand; the system does not disturb human finger movement; the assembly of the exoskeleton and the human finger, have the same variation of movement as the real human finger. Both parts benefits from functional textiles which embeds knitted electrodes.

The benefits from therapeutic electrical stimulation and the exoskeleton driven movements can result in improving muscle tone and prevents muscle atrophy, reduced spasticity, improving blood circulation and skin health.

Our future plans aim to perform different tests within clinical environment in order to prove the effectiveness of the proposed system in the rehabilitation process of stroke patients.

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TESTE PRELIMINARE ALE UNUI NOU DISPOZITIV ASISTIV DE TIPUL FES-EXOSCHELET PENTRU REABILITAREA MEMBRELOR SUPERIOARE IN CAZUL PACIENTILOR CARE AU SUFERIT UN ACCIDENT VASCULAR CEREBRAL

(Rezumat)

Neuroplasticitatea este procesul de recuperare funcțională în urma unei leziuni nervoase, constând în reorganizarea țesuturilor nervoase pe baza formării de noi conexiuni între neuroni şi sinteza de noi celule. Această lucrare propune două noi dispozitive ce deschid noi căi în recuperarea funcțională a membrelor superioare în cazul persoanelor cu dizabilități neuromotorii, membre ale căror funcții au fost pierdute total sau parțial în urma unui accident vascular cerebral (AVC), leziuni la nivelul capului, ale măduvei spinării, etc. Sistemele propuse combină structuri mecanice de tipul exoschelet cu dimensiuni antropometrice şi tehnologia de stimulare electrică funcțională. Aceste sisteme au un design modular şi reconfigurabil, fapt care le face să fie adaptabile pentru ambele membre superioare. Rolul procesului de reabilitare asistat de roboți este esențial în orice sistem de sănătate datorită reducerii costurilor tratamentelor de reabilitare