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DESIGN AND IMPLEMENTATION OF AN EEG-BASED BCI PROSTHETIC LOWER LIMB USING RASPBERRY PI 4

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This paper presents a design and implementation of a mind-controlled prosthetic lower limb prototype to help leg amputees who lost their lower limbs due to different reasons. The system contains a prosthetic lower limb equipped with two servomotors, a motor driver module, a Raspberry Pi, a neuro-headset, and a computer. The prosthetic lower limb prototype is a low-cost 3D-printed prosthetic controlled by brain signals. The prototype has two degrees of freedom for the knee and ankle, which are flexion, extension, plantarflexion, and dorsiflexion. The implemented prototype has been tested on a healthy subject in real-time using the detected brain signals.

Keywords: Brain-Computer Interface (BCI); Electroencephalography (EEG); Prosthetic lower limb; Raspberry Pi; Emotiv Insight

1. Introduction

The original objective of creating the "Brain-Computer Interface (BCI)" technology was to examine the value of employing brain waves in the communication of a human-computer and for medical purposes like movement's restoring [1]. At the same time, this initiative created a novel instrument for the study of neurophysiological mechanisms that manage the creation and regulation of visible neuroelectric events [2]. To collect the electrical signals produced by the brain, electrodes can be implanted directly inside the brain or placed on the scalp.

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Implanting the electrodes on the brain involves one or more surgeries, but the quality of the received signal is excellent.

The scalp, the cortical surface, or even the interior of the brain may all be used to detect electrical signals generated by the neurons. Without the use of nerves or peripheral muscles, a person with a BCI can interact with others [3]. Related to the external device controlling, BCI technology is a two-part process, requiring both the brain and an external device with an interface that allows the activation of a communication channel between the brain and the external device [4].

Individuals with debilitating neuromuscular diseases, like “Amyotrophic Lateral Sclerosis (ALS)”, brain stroke, spinal cord damage, and cerebral palsy, may benefit from BCIs since they do not rely on neuromuscular control where a direct link is established between the brain and the central nervous system [5].

BCI development aims to help people with paralysis or neuromuscular illnesses interact with their environment using software like word processors and other applications and even operate prosthetic devices like robotic arms, legs, and neuro-prostheses. It also provides new approaches to the recovery of stroke patients [6].

Several different signal sources or approaches may be used to capture brain activity, and these approaches involve artificial intelligence software and hardware components forming BCI systems [7]. An electrogram of the electrical activity produced by the human brain is recorded using Electroencephalography (EEG), a non-invasive procedure that forms the basis of BCI technology. Electrodes attached to the scalp record electrical activity in the brain. This approach was first developed to identify and treat disorders of the brain and mind. This method monitors the fluctuation in neuronal membrane potential due to changes in ionic current by using electrodes placed on the scalp.

Many people who have lost a lower limb depend on prosthetic legs to help them in their daily regular activities. Prostheses have advanced to the point that they may effectively replace missing limbs or organs while being cosmetically unnoticeable. Commercially accessible transtibial prostheses have advanced, but even the most cutting-edge models still only alter the ankle position passively during the walking phase of swing and return the user’s gravitational input part [8]. A robotic ankle prosthesis that can function comparably to or even better than the equivalent of an able-bodied human ankle will considerably enhance the quality of life of transtibial amputees.

A prosthetic lower limb can be controlled using a microcomputer, by attaching servo motors and a motor driver module with a power source to the prosthesis. “Raspberry Pi 4 Model B” is a good option to provide good performance to control the prosthesis device.

The goal of this research is to make a lower limb prosthesis using a 3D printer to build a prosthesis limb with a controlling system through a neuro-headset. To control the prosthetic leg, the EEG signals captured from the brain signals will be converted to specific commands to move the prosthetic leg.

The use of materials like Polylactic Acid (PLA) in 3D printing is often used in a variety of medical applications, including surgical, implants, prostheses, and others [9], [10]. This method of 3D printing will reveal the next generation of medical prosthesis devices since a new type of material will be available [11]. To the best of our knowledge, the proposed prototype is the first of its type in Romania.

2. Literature review

There are several sources in the literature related to the use of brainwave signals for controlling prosthetic upper or lower limbs.

The approach of using EEG signals was successfully used by Muhammad Yasin et al. [12] in which dorsiflexion and plantarflexion movements of an ankle prosthesis were controlled by EEG signals recorded from channels C3 and C4. The prototype they used was an updated version of a 3D model available as an open-source printed using PLA. The system may either operate in the motor execution mode or the motor imagery mode. Two healthy males participated in the experiment where the results showed that the top accuracy was 33.33% for subject 1 in motor execution mode and 38.89% for subject 2 in motor imagery mode.

Ou Bai et al. [13] have presented a developed portable prototype battery-operated device that can simultaneously interpret data from several EEG channels and send that information wirelessly. The user's intentions may be deduced from EEG data using signal processing and machine learning algorithms, used to control the user's prosthetic. The participant was a right-leg amputee taking part in a feasibility study. The results show that the lower-limb amputation user was able to move a prosthetic knee actively with a sensitivity of 83% and no false positives.

The same method of capturing and interpreting EEG signals was successfully used by Elstob et al. [9]. They proposed a system to control a 3D-printed upper limb prosthetic device. They used an EMOTIV™ EPOC+ EEG neuro-headset to record brain activity and an Arduino Uno microcontroller to control the device.

Using a BrainBoard, Douglas P. Murphy et al. [14] created an EEG hardware prototype for recording EEG and electromyogram (EMG). The BCI system uses a brain cap to detect the brain’s signals. A specialized program interprets these signals as instructions that are sent to the Mainboard to operate the prosthetic leg. Based on data from eight different experiments, the rate of success for releasing the mechanism of the prosthetic knee is greater than 50%.

To support individuals with impairments (like a stroke, spinal cord damage, or other), An H. Do et al. [15] proposed a BCI "Functional Electrical Stimulation (FES)" system to assist restore or enhance motor behaviours. The suggested system consists of an electro EEG hat, a pair of ankle-mounted electro goniometers, and a Mainboard. Experiments revealed that all participants achieved a complete BCI-FES response.

Methods for studying and decoding intent from behavioural data were described by Hongbo Gao et al. [16]. The prosthetic lower limb used is mimic the gaits of a natural lower limb so that it may be used on the ground, stairs, and the floor. They used "NuAmps NeuroScan 40-channel" device to collect EEG data. The prosthetic limb's executive and sensing system is constructed with the above components. The box plot confirms the results of the confusion analysis, showing that the median categorization accuracy for hands is more than 80%, while it is lower for feet (about 70%). And across all three imaging tasks, the median classification accuracy was 81%, which is much over the 33% threshold of statistical significance.

A review of the literature revealed that the combination of BCI with prostheses is a novel and rich area of research. Additionally, it was discovered that modifications are required to raise control effectiveness while reducing the system's complexity. This study suggests a solution that employs a Raspberry Pi 4 alone, without an Arduino board, and without using external Wi-Fi modules. Table 1 shows the differences between this work and other related works.

Table 1

Related works

Title	Advantages	Disadvantages	What is different in this work
"Ankle Prosthesis With Brain Computer Interface Commands Based on Electroencephalograph for Transtibial Amputees" [12]	1. Real-time system 2. Non-clinical risks 3. The prototype has been made from strong material	1. Complex and unaffordable EEG recording unit 2. Controlling only the ankle's movement	1. Affordable and comfortable EEG unit has been used 2. Controlling ankle and knee movements 3. Motor execution mode is not needed in this work
"Brain-computer interface controlled functional electrical stimulation system for ankle movement" [15]	1. Real-time BCI system 2. Good accuracy of response	1. Only ankle rehabilitation	1. Ankle and knee movements simulation
"Online multi-class brain-computer interface for detection and classification of lower	1. Real-time BCI system 2. Affordable 3. Detector with good	1. Algorithm with low accuracy 2. No prototype was implemented	1. Good accuracy

limb movement intentions and kinetics for stroke rehabilitation" [17]	accuracy		
"A wireless, smart EEG system for volitional control of lower-limb prosthesis" [13]	1. Affordable 2. Real-time BCI system 3. Lightweight materials 4. Low power consumption	1. One EEG sensor (not accurate signal) 2. Controls knee movement only	1. Five EEG sensors (accurate EEG signal) 2. Controls knee and ankle movement
"Electroencephalogram-based brain-computer interface and lower-limb prosthesis control: A case study" [14]	1. Affordable 2. Real-time BCI system 3. Good accuracy of response 4. Low power consumption	1. Controls knee movement only 2. Study case only, no prototype implemented	1. Controls knee and ankle movement
"EEG-based volitional control of prosthetic legs for walking in different terrains" [16]	1. Real-time BCI system 2. Good accuracy of response 3. Sensory feedback	1. Unaffordable	1. Affordable

3. Materials and methods

This section presents the design, used materials, and implementation of the proposed system. The implemented prosthetic leg is not designed to be used by a human; it is only a proof-of-concept system's prototype for further research purposes. In the future, some testing can be done on this prosthetic leg by creating a special support to measure how the leg reacts to forces. The block diagram of the system mechanism is presented in Fig. 1. In the next sections are presented hardware components.

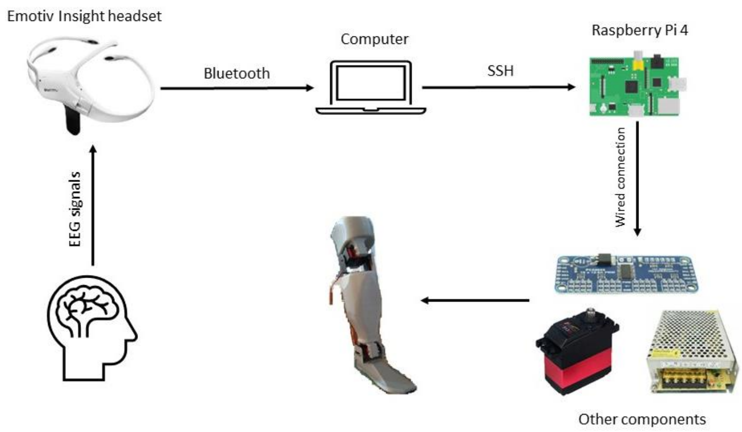

Fig. 1. System architecture

3.1. Computer

The main purpose of the computer (see Fig. 1) is to process the EEG signals using Python language and EMOTIV Cortex API and to send commands to the Raspberry Pi. The brain signals detected by the neuro-headset are automatically converted (feature extraction and classification) by Cortex API into commands on the computer side. The resulting commands are sent further to the Raspberry Pi. The noise in these signals is removed by a Sinc filter, which is inside the headset [18]. The Sinc filter is based on the concept of a low pass filter with a fixed cut-off frequency in mathematics. Signal components with frequencies below the cut-off are not filtered out, while those with frequencies over the cut-off are eliminated [19].

The computer processing part is needed because the EMOTIV Cortex API currently does not support Linux OS. The computer can be eliminated from this system when EMOTIV Cortex API will support Linux OS.

3.2. Microcomputer

The selected microcomputer to be used in the proposed system is "Raspberry Pi 4 Model B", which offers high-level processing speed and performance (see Fig. 2) [20].

3.3. Neuro-headset EEG based

"EMOTIV™ Insight neuro-headset" has been used in this system to record the EEG signals. The headset contains five semi-dry polymer electrodes. It has a sampling rate of 128 Hz per channel.

The EEG signals are filtered, and the data is sent wirelessly to the computer for further processing, making this equipment ideal for BCI research and experiments. The neuro-headset uses Bluetooth Low Energy or 2.4 GHz wireless connectivity to connect with a computer, mobile phone, or tablet. The headset is designed to operate for up to 8 hours due to its 450 mAh LiPo battery. To record the brain signals, the neuro-headset must be placed on the head's scalp, where the raw EEG data are transferred to the computer wirelessly (see Fig. 2) [21].

3.4. Servomotor

The motor used in this system is FT513BL servomotor brushless (see Fig. 2). This servomotor is suitable for projects that require high torque. It is connected to the motor driver module since 6V~7.4V is required to operate the servomotor. In the proposed system it was used two servomotors.

3.5. Motor driver module

"16 Channel I2C PWM Motor Driver Module" is a PCA9685, which is a new Fast-mode Plus family that offers up to 1 MHz frequency, and can control several servomotors (see Fig. 2). 5V is the input voltage required to operate this driver module [22].

3.6. Power supply

“5 V 10 A (50 W) Switched Mode Power Supply” is the selected power source for the proposed prototype (see Fig. 2). This power supply is perfect for keeping voltage stability.

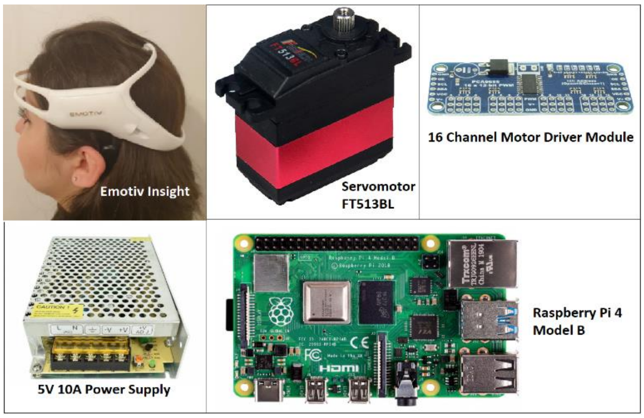

Fig. 2. System hardware components

3.7. Prosthetic lower limb

Using the SolidWorks Computer-Aided Design (CAD), a prosthetic leg with three components was designed: foot planetary area, calf, and knee (see Fig. 3).

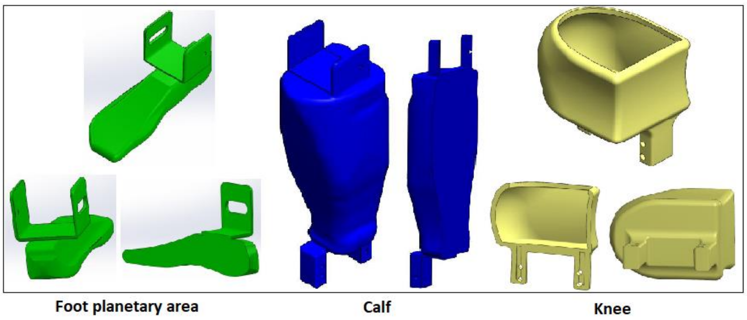

Fig. 3. Design of the prosthetic lower limb components in SolidWorks CAD

The three designed components were printed using a 3D printer, and the material used for printing was PLA (see Fig. 4). PLA is a biodegradable, robust, and lightweight polymer which makes it an excellent choice for the proposed system. The project is primarily focusing on moving the prosthetic lower limb with a neuronal headset in real-time and maintaining a low-cost system implementation.

Fig. 4. Prosthetic lower limb PLA components

4. Implementation of the system

The system consists of several parts, and they are connected as the following: the neuro-headset EMOTIV Insight is connected to the computer via Bluetooth, the computer is connected to the Raspberry Pi 4 via Secure Shell Protocol (SSH), and Raspberry Pi 4 is connected to the prosthetic lower limb through the GPIO pins.

First, the 3.3 V GPIO pins of the Raspberry Pi 4 are connected to the VCC pin of the motor driver module. GPIO 2 pin (I2C Serial Data) is connected to the SDA pin of the motor driver module. GPIO 3 pin (I2C Serial Clock) is connected to the SCL pin of the motor driver module. The ground pins of each Raspberry Pi 4 and the motor driver module are connected. In this context, the servomotors are connected to the motor driver module, where each motor is connected to one channel of the motor driver module. The signal wire of the first servomotor is connected to the PWM pin of channel 0, the voltage input to the servomotor is connected to the V+ pin of channel 0, and the ground of the servomotor is connected to the ground pin of channel 0. The same connection is applied to the second servomotor with channel 1. The external power supply is connected to the motor driver module to provide the necessary power for the system (see Fig. 5).

The brain signals are sent from the neuro-headset to the computer wirelessly to perform signal processing. Noise and artifacts need to be removed or at least reduced from the raw EEG signals by applying digital filters, then, these signals are sent to the Raspberry Pi 4. On the Raspberry Pi, two python scripts have been written to control knee and ankle movements of the prosthetic lower limb through two servomotors. The python scripts on the Raspberry Pi 4 can be shown in Fig. 6, which illustrates how can GPIO pins can be configured using the "adafruit_servokit" library.

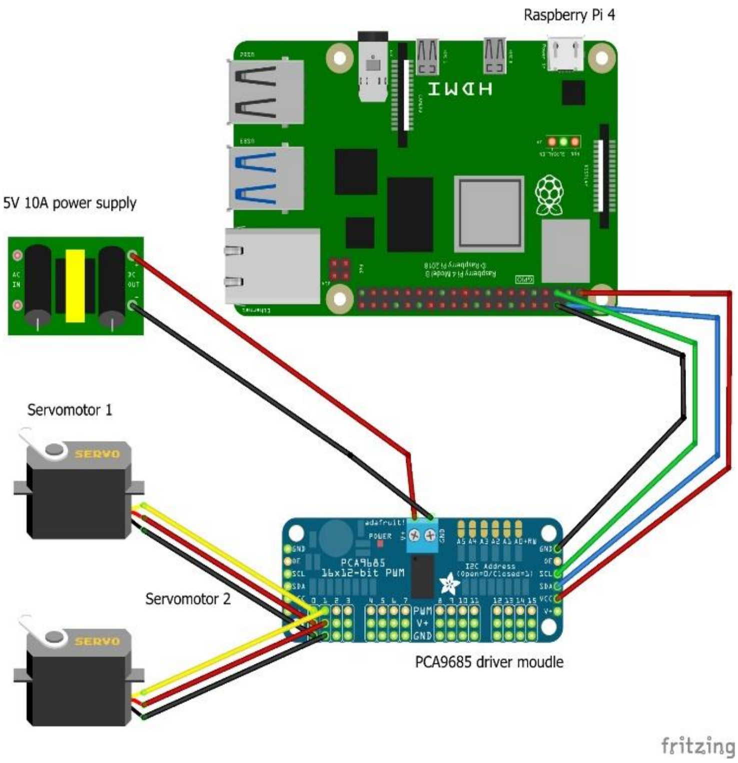

Fig. 5. Diagram of the system circuit

```
from time import *
from adafruit_servokit import ServoKit
kit = ServoKit(channels = 16)
sleep(2)
kit.servo[3].angle = 70
```

```
from time import *
from adafruit_servokit import ServoKit
kit = ServoKit(channels = 16)
sleep(2)
kit.servo[2].angle = 70
```

Fig. 6. Python code for moving the knee flexion and ankle plantarflexion

To synchronise the movement between the knee and ankle of the prosthetic lower limb, two brain commands have been trained to control plantarflexion, dorsiflexion movements of the ankle, and flexion, extension movements of the knee. To move the prosthetic lower limb, the user must wear the neuro-headset and motor imagery of the dorsiflexion, extension, plantarflexion, and flexion movements (see Fig. 7). By doing this, when the user thinks, the signal will be transmitted from neuro-headset to the computer and then to the Raspberry Pi 4 to run the required python scripts.

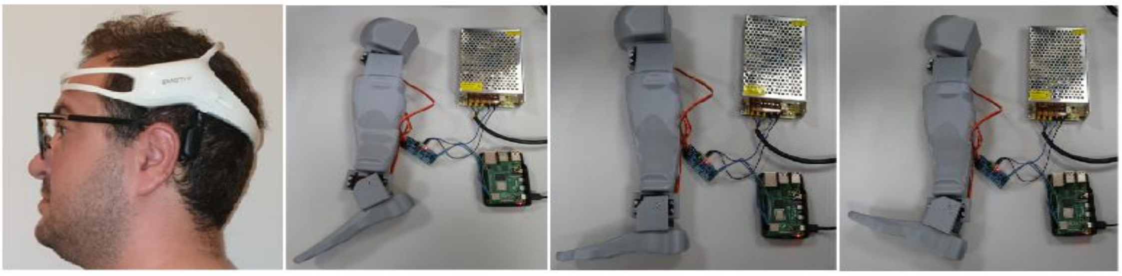

Fig. 7. Subject controlling the prosthetic lower limb prototype

5. Results

The testing of the system was conducted using EEG signals recorded from a healthy male subject.

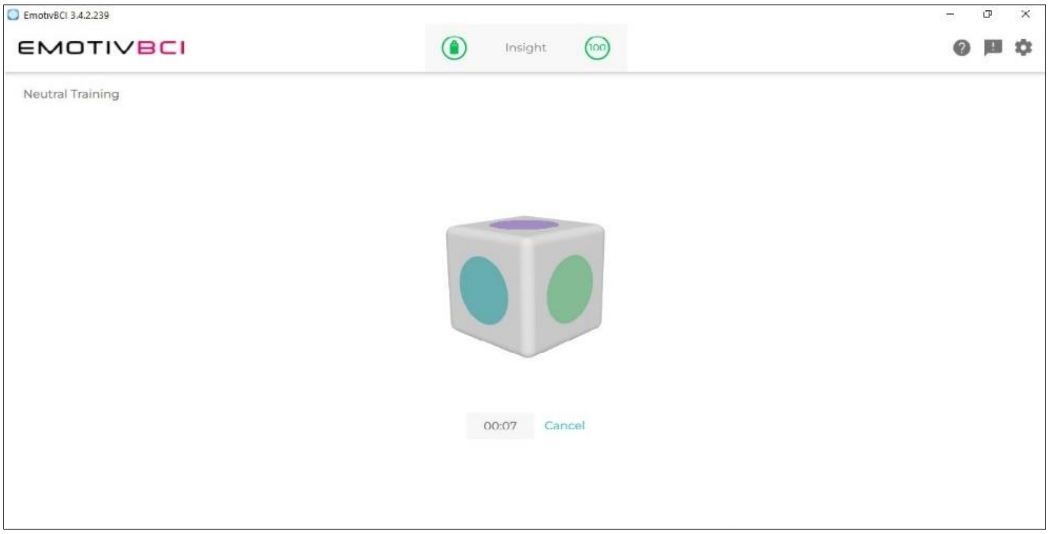

Fig. 8. Session training of the subject

To enable the subject to control the prosthetic lower limb, the subject must wear the headset and train two commands to provide the necessary control for the movements. Emotiv BCI application has been used for the training process, where each command has been trained 40 times. The duration of each time is eight seconds.

The training session takes about 20 minutes (see Fig. 8). After the training, the subject was asked to control and do flexion, extension, plantarflexion, and dorsiflexion movements of the prosthetic lower limb using his thoughts as shown in Fig. 7.

The performance of the prosthetic leg regarding movement can be measured and evaluated by creating a stand as shown in Fig. 9.

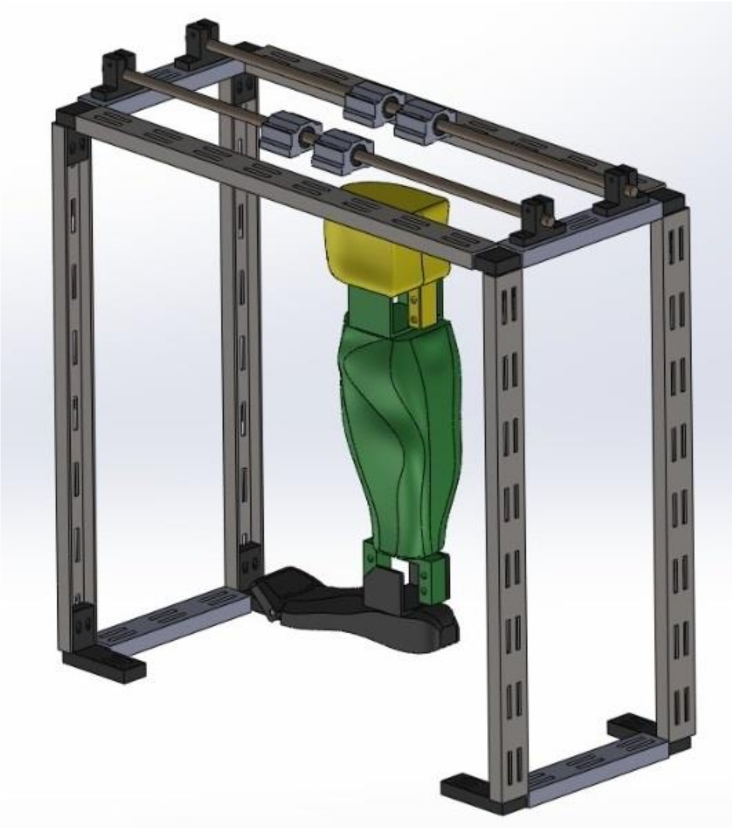

Fig. 9. 3D stand prototype to measure the prosthetic leg movement performance

Compared with other advanced headsets that contain many electrodes, the performance of the system is relatively good regarding the EEG signal obtained from the neuronal headset since it provides the desired decoding and processing for brain signals.

6. Conclusion

The use of the EEG-based BCI method is relatively a new direction of research, particularly in the medical domain.

This paper presents the design and implementation of a mind-controlled prosthetic lower limb prototype. The materials used to create the prosthetic device are both robust and lightweight materials. To simulate the regular movements of a human leg, the prototype uses two servomotors controlled by a Raspberry Pi 4 Model B. In conclusion, the project's prototype system has been built using EEG-based BCI technology and all its intended aims have been achieved.

The original contribution for this paper is defined by the designing, implementation and hardware equipment of the 3D printed prosthetic lower limb, and to control this prosthetic leg using brain commands. As far as we know, this system is the first of its type in Romania.

In future work, the prototype should come up with a better design for adding fingers, and for replacing the external power source with a battery included in the calf of the prosthetic lower limb. A more accurate EEG device can be used to improve the accuracy of EEG signals. More freedom degrees for ankle rotation should be considered, also, more tests can be performed on the prototype using a special testing stand (see Fig. 9). The computer should be eliminated from the system when Cortex API supports Linux OS. This will enable Raspberry Pi 4 to handle all the processing part and control actions.

Also, as future work, a prosthetic leg at an adult human scale can be implemented to be tested on amputees.

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