



Hardware Article

A lower limb rehabilitation platform with mirror therapy, electrical stimulation and virtual reality for people with limited dorsiflexion movement



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ABSTRACT

This paper presents a low-cost portable system for applying a rehabilitation therapy, based on virtual reality, functional electrical stimulation and a training device. This open-hardware system, intended to support a home-made therapy process in people with reduced dorsiflexion ability, contains three main building blocks: an electromechanical platform, an immersive virtual reality interface and the firmware. The electromechanical training platform is the core of the system, which acts as a gateway interface of sensors-actuators for a closed loop system, through an immersive virtual reality application, the patient closes the loop by acting as the controller by means of a “virtual dummy” preforming in mirror configuration.

The platform measures and process the dorsiflexion angle described by both ankles, real-time transmitting the information to the mobile phone virtual application to be presented as a mirror. The onboard microprocessor drives the operation of the electric stimulation interface, which is sent through two channels to both, healthy and affected lower limbs. The platform communicates continuously through a USB bidirectional interface with a personal computer, in which the physician enters the rehabilitation protocol and follows the patient performance. A first case study by using this device has been reported in [1].

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Specifications table

Hardware name	DorsixRehab
Subject area	<ul style="list-style-type: none"> • Medical (Physiotherapy)
Hardware type	<ul style="list-style-type: none"> • Rehabilitation technology (Tools that help people regain function after injury or illness) • System for measurement of biomechanical variables • Electrical engineering and computer science

(continued on next page)

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Closest commercial analog
Open source license
Cost of hardware
Source file repository

No known commercial analog is available.
 Creative-Commons.
 USD 440
 Link to data in Mendeley Reserved DOI: 10.17632/bx2zyxjzsb.1

1. Hardware in context

Human gait uses repetitive movements in the lower limbs to advance the body. Some pathologies led to muscle weakness, sensory loss, and impaired motor control, thus affecting balance in people due to decreased movement and asymmetry in movement. The majority of the patients with impaired dorsiflexion adopt compensatory strategies such as excess hip movement and decreasing rocking of the affected limb during gait [2], hence restoring the independent walking ability is a priority in the rehabilitation process [3]. Different investigations present rehabilitation approaches aimed at the recovery of the lower limbs, such as the mirror therapy (MT) [4], which is based on the use of a mirror to create the reflective illusion of the affected limb. The healthy limb performs movements that are reflected as if they were made by the affected limb [5]. Functional electrostimulation (FES) is a rehabilitation method that applies electrical impulses to a muscle that is weak or paralyzed and thus generates muscular contractions in a coordinated way, with functional movement patterns favouring motor relearning [6]. Immersive virtual reality (IVR) [2], presents a virtual environment in which the patient visualizes movements of the limb “fooling” the brain that what is happening is their own reality [7].

Some studies on the combination of MT with VR have shown effectiveness in the lower limbs rehabilitation process, this type of application allows hiding the affected limb and replacing it with a virtual one where movements are simulated in a virtual space. Capture sensors, e.g., cameras detect movements in the healthy limb which is replicated by the affected limb in the virtual environment [8,9]. Another type of combination is the MT with FES which uses the mirror box in conjunction with an electrostimulator, it is mainly characterized by performing programmed exercises in the MT. The intention of movement is captured by means of electromyographic signals which activate the stimulator device by applying electrical pulses to the affected limb, while the patient observes the reflected movement of the healthy limb [3].

For the case of the combination of VR with FES, it is applied for the recovery of posture and body balance. This technique allows the body to be visualized on a screen by identifying the lateral deviation with respect to the central position of the body, when some type of deviation occurs, an electrical impulse is generated on the affected limb so that the person returns to its state of natural balance [10].

Although some rehabilitation applications can be found in the scientific literature through the application of some of the aforementioned technologies, there are no commercial devices intended to be used by patients or researchers that combine these technologies or approaches. Furthermore, most of the research results already published have been carried out on prototypes developed ad hoc for the purposes of each project. In addition, these devices do not consider a comprehensive process that can provide all the already known benefits of these rehabilitation approaches and devices.

A known limitation in the rehabilitation processes, for example in the post-stroke case, is the loss of mobility and the difficulty in moving to the therapy site, especially if treating patients in developing countries, where the health is limited for the population. In this context, it is necessary to develop therapeutic alternatives to treat people at home, where it is not necessary to travel to specialized rehabilitation sites to do the therapies, all this through low-cost technology, which can be assumed by entities or even by patients.

This work describes a low-cost portable system for rehabilitation that combines mirror therapy with an immersive virtual environment, in conjunction with the application of functional electrical stimulation, with the purpose of recovering the dorsiflexion movement of the ankle in a patient who has lost partial or full range of motion. The DorsixRehab system was initially designed for conducting research activities, but it can be used in other contexts, according to the requirements of a diverse range of applications.

2. Hardware description

An electromechanical system with IVR is developed under the concept of MT for the recovery of dorsiflexion movement in lower limbs. The Fig. 1 shows the block diagram of DorsixRehab system. The training platform consists of a cuboidal structure, which has two bases that support the feet of the person who performs the dorsiflexion movement, these bases are supported by bearings that allow angular movement of the ankle, each base has a plastic boot, that restricts pronation and supination movement of the foot. Each bearing is linked to a linear potentiometer which acts as dorsiflexion angular motion sensor. Additionally, a couple of supports were created through 3D printing to join the sensors to the bearings. A microprocessor unit (MCU) ATMEGA 328P (1), implemented on an Arduino nano development board, is responsible for capturing the analog signals from sensors and then converts them into the corresponding dorsiflexion angular values. For the application of the FES, a commercial electrostimulator (EMS 5.0) (5) was used, which is modified to control the intensity of electrical stimulation, contraction time and relaxation by means of digital potentiometers. These potentiometers are driven directly by the MCU, which communicates with a computer application (1) through the serial communication protocol using the USB communication bus. In this way, the user of the desktop interface (it can be medical personnel, the patient’s relatives,

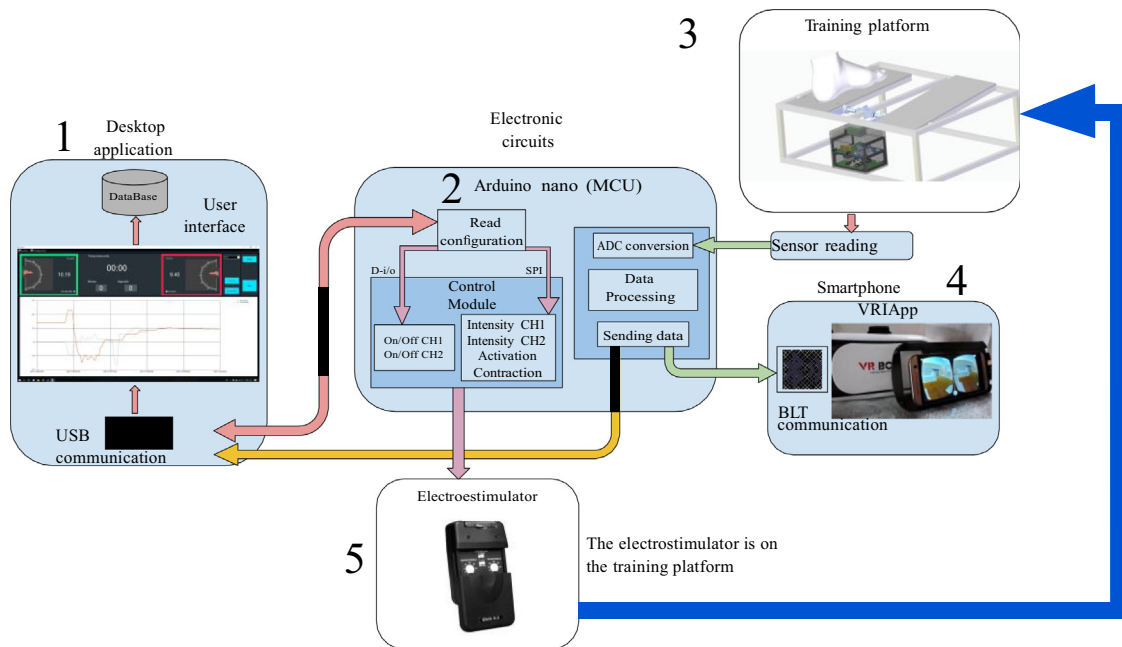


Fig. 1. Block diagram of the conceptual building blocks of DorsixRehab system.

etc.) can configure the behaviour of the application of the electrical stimuli, the rehabilitation time and in addition, visualize the curves of the dorsiflexion and evolution work of therapy in real time.

To increase the usability and portability, the IVR application was developed so that it can run on any commercial smartphone device (4), as long as it has an inertial measurement unit (IMU) and a Bluetooth device. Communication between the mobile device and the rest of the system is done through the Bluetooth protocol, therefore an internet connection is not necessary. The MCU is responsible for sending to the mobile device, the angular value of dorsiflexion captured in (3) through a serial Bluetooth module HC-05, information that will be processed and presented graphically in the IVR application implementing the concept of the MT (4).

Key features of the system:

1. The training platform integrates a measurement mechanism for the angular displacement of the ankle, thus providing an accurate metric of the rehabilitation process.
2. The system is portable and can be used at home by any patient with the help of people without physical therapy training, based on the sequences predefined by a professional.
3. The system has two software tools that integrate the entire process, the first one runs on a mobile terminal, with an immersive virtual reality viewer in which the dorsiflexion movement in the lower limbs is displayed by an avatar. The other tool allows to control the entire rehabilitation process, therapy configuration, the recording of the information generated by the dorsiflexion movement and real-time analysis of the stored information.

The Fig. 2 shows the training platform developed for the application of the rehabilitation process in the lower limbs in people with reduced dorsiflexion mobility.

Design files

The online repository Link to data in Mendeley or Reserved DOI: <https://doi.org/10.17632/bx2zyxjzjb.1> contains the files for implementing the DorsixRehab system. The information is summarized next.

CAD files: A CAD model of the platform is designed to verify the measurements and disposition of the movable parts and electronic devices; in Fig. 2b the 3D model of the training platform is observed. The parts that make up the system are shown, validating the measurements of the parts and the position of the components, also verifying that the movement of the bases of the feet is not affected by the geometry of the system. The full set of files can be found under directory ../CAD/ (CAD)

3D printing: Two supports were designed for transmitting the rotational movement from the bearing to the angular movement sensor of the ankle to be measured. Fig. 3 shows the support implemented for each movement sensor, where the brackets are secured to the cuboidal base and angular movement is captured by joining the drive base to the inner ring of the bearing. The full set of files can be found under directory ../3DPrintingFiles/ (3DPrintingFiles)

In addition to the sensor supports, a cover box was also printed for protecting the electronic boards of the system. (Fig. 11).

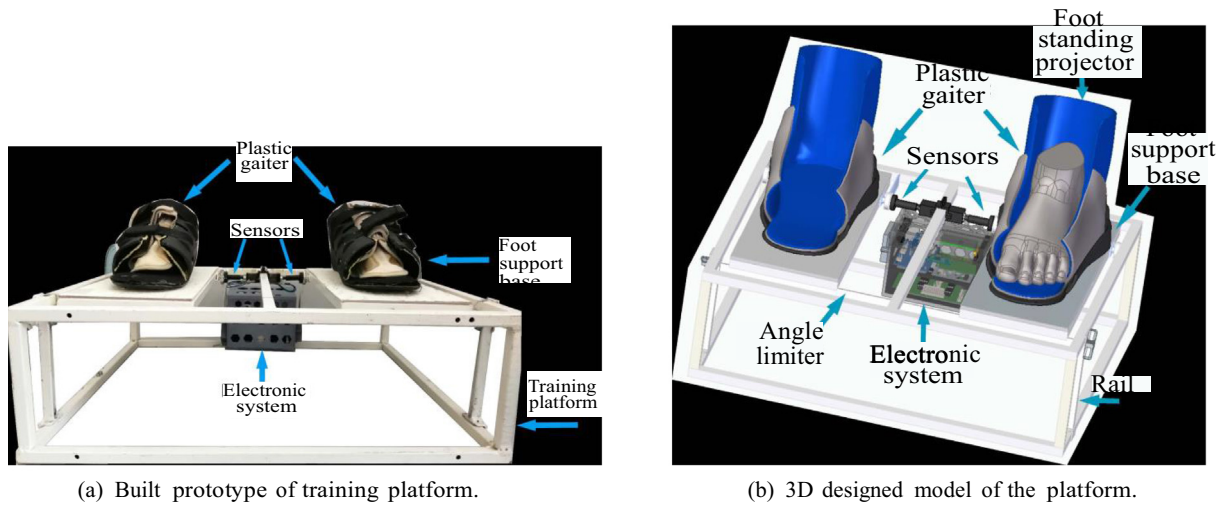


Fig. 2. Main elements of the training platform of DorsixRehab system.

Electronics: The schematic diagram of the electronic circuit is presented in Fig. 4. The components include an Arduino nano, 2 solid state relays, 2 optocouplers, 2 digital potentiometers (20kΩ) and 2 digital potentiometers (10kΩ), 1 HC-05 Bluetooth module and 1 electrostimulator with 2 channels. The electronic system is powered by the USB cable which is connected between the Arduino board and a USB port of a computer. The electrostimulator is powered by a 9V battery. The full set of files can be found under directory ../Electronics/ (Electronics)

Software and firmware: The software and firmware required for the DorsixRehab system operation is composed by three different blocks:

1. The MCU code. The firmware for Arduino is available in the folder ../Firmware/ReadADC/ (ReadADC). The state machine presented in Fig. 5 describes the loop function performed by the MCU.
2. The desktop application for configuration and visualization of the DorsixRehab system (Fig. 13b) is in the folder ../GeneralSW/ (GeneralSW)
3. The IVR app for the mobile phone (Fig. 13a) is in the folder ../VirtualRealitySW/ (VirtualRealitySW)

3. Design files summary

Design filename	File type	Open source license	Location of the file
BaseSupportSensor1.par	CAD file	GNU GPL v2.0	../CAD/
BaseSupportSensor2.par	CAD file	GNU GPL v2.0	../CAD/
BatteryCover.par	CAD file	GNU GPL v2.0	../CAD/
CoverFES.par	CAD file	GNU GPL v2.0	../CAD/
CuboidPlatform.asm	CAD file	GNU GPL v2.0	../CAD/
DiceBase.par	CAD file	GNU GPL v2.0	../CAD/
ElectroBase.par	CAD file	GNU GPL v2.0	../CAD/
Extender.par	CAD file	GNU GPL v2.0	../CAD/
FESBox.par	CAD file	GNU GPL v2.0	../CAD/
PotBase.par	CAD file	GNU GPL v2.0	../CAD/
RotBase.par	CAD file	GNU GPL v2.0	../CAD/
Design.pd sprj	CAD file	GNU GPL v2.0	../Electronics/
StateMachine.ino	ARDUINO file	GNU GPL v2.0	../Firmware/ReadADC/
Linearization.cpp	C file	GNU GPL v2.0	../Firmware/ReadADC/
Linearization.h	C file	GNU GPL v2.0	../Firmware/ReadADC/

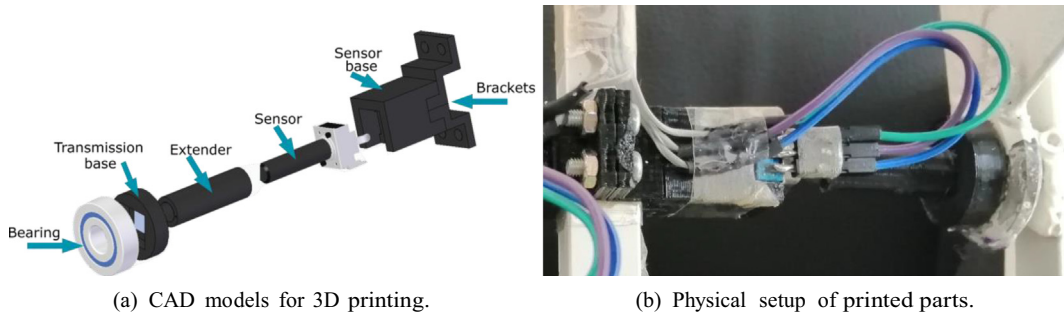


Fig. 3. Supports for the angular movement sensors.

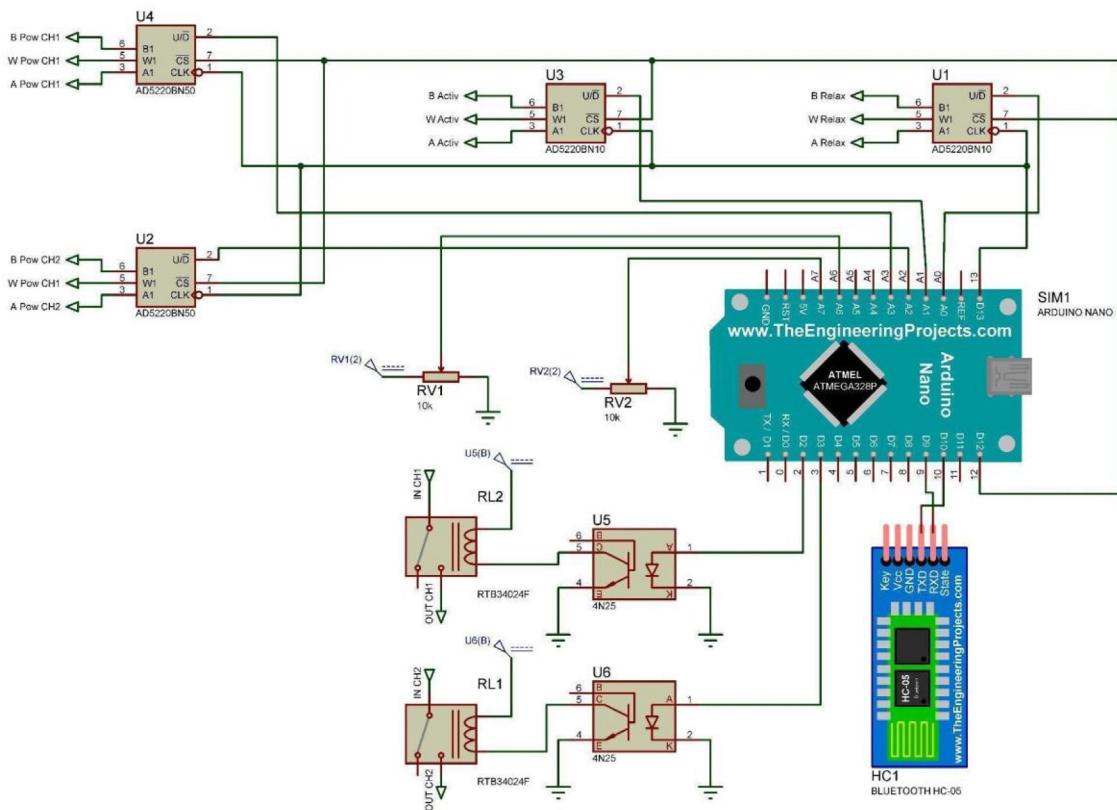


Fig. 4. Electronic diagram for the DorsixRehab system, considering MCU connections, Bluetooth module and I/O modules.

BaseSupportSensor1.par:

3d model of connection support between the training platform and the sensor base.

BaseSupportSensor2.par:

3d model of connection support between the training platform and the sensor base.

BatteryCover.par:

3d model of the box that stores the battery for the operation of the electro stimulator

CoverFES.par:

3d model of the lid for the box containing the electronics.

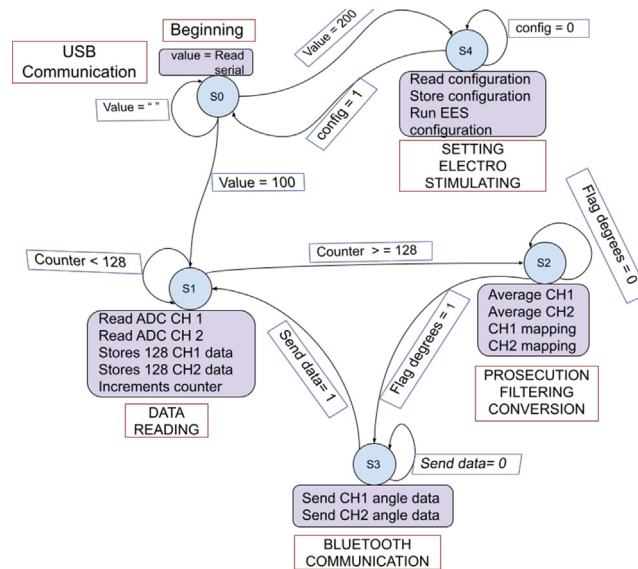


Fig. 5. State machine implemented in firmware.

CuboidPlatform.asm:
Training platform 3D model.

DiceBase.par:
3d model of the connector between the foot platform base and the extender

ElectroBase.par:
Base that supports the electrostimulator.

Extender.par:
Motion transmitter 3d model between foot swipe and sensor.

FESBox.par:
3d model of the box that stores the electronics of the system.

PotBase.par:
3d model of the base where the sensor is located.

RotBase.par:
3d model of the rotational base located in the ball bearing.

Design.pdsprj:
Schematic model and connection of the electronic components that make up the system.

StateMachine.ino:
State machine model with which the firmware was developed.

Linearization.cpp:
Class containing the functionalities required for the angular processing of the foot movement in the firmware

Linearization.h:
Library containing the declaration of the functionalities required for the angular processing of the foot movement in the firmware.

4. Bill of materials summary

Designator	Component	Number	Cost per unit – USD	Total cost – USD	Source of materials	Material type
C1	Tube 1 platform	4	1.2	4.8	C1 link	Metal
C2	Tube 2 platform	4	1.2	4.8	C2 link	Metal
C3	Tube 3 platform	4	1.2	4.8	C3 link	Metal
C4	Tube 4 platform	4	1.2	4.8	C4 link	Metal
C5	Angular graduation bar	1	4.78	4.78	C5 link	Metal
C6	Rail for angular graduation	2	4.78	9.56	C6 link	Metal
C7	Wing nut	2	0.66	1.32	C7 link	Metal
C8	tube 1 foot base	2	1.2	2.4	C8 link	Metal
C8	tube 1 foot base	2	1.2	2.4	C9 link	Metal
C10	Acrylic plate	2	19.99	39.98	C10 link	Acrylic
C11	Bearing 6201 2RS	2	7.45	14.9	C11 link	Metal
C12	Axis of rotation	2		0		Metal
C13	base-bearing connector	2		0		Plastic
C14	Sensor base	2		0		Plastic
C15	Connection plate	2		0		Metal
C16	Extender	2		0		Plastic
C17	Linear potentiometer	2	1.02	2.04	C17 link	Metal – Semiconductor
C18	Sensor bracket	2		0		Plastic
C19	Top bracket	2		0		Plastic
C20	Bottom bracket	2		0		Plastic
C21	Plastic gaiter base	2	89	178	C21 link	Plastic
C22	plastic gaiter protector	2		0	C22 link	fabric – foam
C23	2 position molex connector	4	0.86	3.44	C23 link	Metal – Semiconductor
C24	3 position molex connector	6	0.86	5.16	C24 link	Metal – Semiconductor
C25	Arduino Nano MCU	1	22	22	C25 link	Metal – Semiconductor
C26	10 position molex connector	1	0.98	0.98	C26 link	Metal – Semiconductor
C27	CH-05 Bluetooth	1	18.5	18.5	C27 link	Metal – Semiconductor
C28	Digital potentiometer 10kΩSPI MCP41010-I/SN	2	6	11.706	C28 link	Metal – Semiconductor
C29	Digital potentiometer 50 Kohm SPI MCP41050-I/SN	2	6	11.706	C29 link	Metal – Semiconductor
C30	Optocoupler 4n25	2	0.81	1.62	C30 link	Metal – Semiconductor
C31	Solid state relay 5v SSR PCB G3MB-202P DC-AC	2	18.26	36.52	C31 link	Metal – Semiconductor
C32	Electro stimulator	1	53.51	53.51	C32 link	electronic circuit

All materials and elements required for building this system are available and easily accesible. Links in this table point to common online stores (US mainly). However, the prototype shown along this paper was built in a small city in a developing country, and all the elements were bought from local physical stores.

5. Build instructions

5.1. Training platform

Square metal tube is selected as the material for the construction of the cuboidal base, since the system needs to have the necessary strength to support the weight of the lower limbs when the dorsiflexion movement is being generated. No corrosion studies have been conducted on this material; however, this system is intended for indoor use only, and must be operated in a clean, dry environment (a living room or a bedroom, for example). For the construction of this base, which is the

support of the training platform, the pieces that are connected with the red arrows must be joined with electric welding: as indicated in Fig. 6 components C1 and C2 should have a 45° cut at the ends. The parts indicated with green arrows, are parts that can be placed and removed, these parts C5, C6 C7 allow the angle at which the measurement process starts to be adjusted, the horizontal position of the base of the foot corresponds to angle 0°, the selected convention is positive angles for up position and down position for negative angles. The measurements and location of each component are detailed in the figures located at ../Schematics/ folder, corresponding to the top, front, and side view of the cuboidal base.

The base that supports each foot and allows the angular movement of dorsiflexion, is built with the parts indicated in Fig. 7, the inner ring of the C11 is attached to a C12 shaft, one of these shafts is used to connect the sensor base C14 to capture the dorsiflexion movement of the foot, the outer ring of the bearing, which is connected to the outer part of the base, is attached to C2 tube of the cuboidal base, the outer ring of the bearing on the opposite side base is attached to C15 plate, which is connected to the C1 tube achieving the necessary resistance to support the feet. The points marked in red are joined to the base with a quick-drying glue. In order to improve the contact between the metallic base and the floor, a small piece of rubber material can be added under the cuboidal base.

The location of the liner holding the foot is shown in Fig. 8a, the C21 plastic base is attached to the C10 acrylic base with screws or quick-drying glue, the C22 protection is inserted into the C21 plastic liner together with the foot of each lower limb. To obtain the plastic gaiter an ankle splint or an inline skate boot is modified, since these are similar in design and the material with which they are constructed. The toe of the boot and the parts that support the heel must be cut to allow for angular movement of the foot. Velcro fasteners are used to secure the foot in order to avoid involuntary movements of the toes and to ensure that the captured angular movement correspond to the dorsiflexion of the foot. Fig. 8b shows the parts that need to be removed to obtain the plastic gaiter.

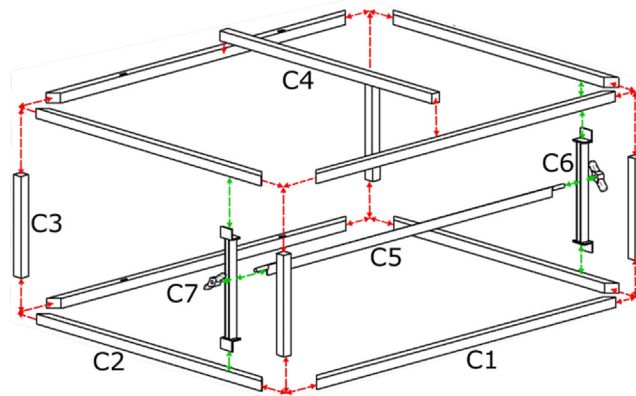


Fig. 6. Metallic structure to support for training platform.

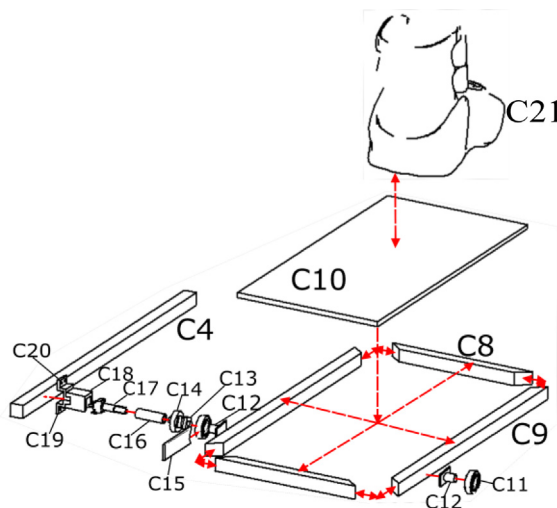
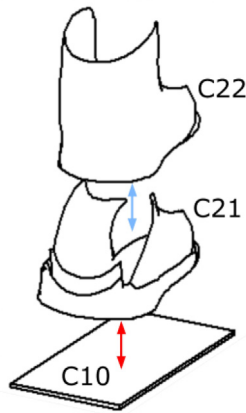
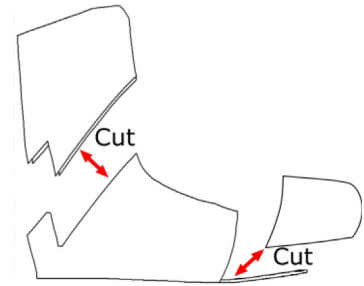


Fig. 7. Assembly to join the foot base to the cuboidal platform.



(a) Attaching the plastic gaiter to the foot support base.



(b) Cuts for the plastic gaiter.

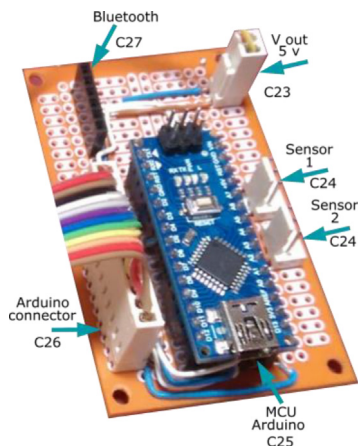
Fig. 8. Physical setup for attaching the moving platforms to plastic gaiter.

5.2. Electronics

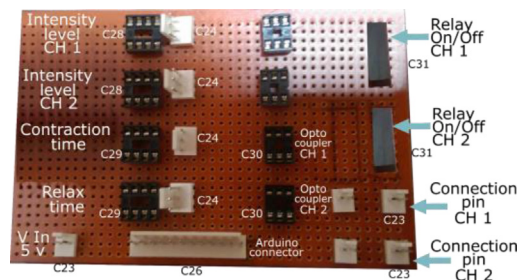
Control board: The Arduino nano is located on the board, which connects with the control module through the C26 connector, a connector for powering up and communication with the C27 Bluetooth module 3-pin C24 connector for reading the sensors angular motion switch and a 2-pin C23 connector to power the control board. Fig. 9a shows the connection of the components with the MCU Arduino board.

Power and regulation card: The digital potentiometers, optocouplers and solid state relays are located in the arrangement shown in Fig. 9b, a 10-pin connector C26 is responsible for the communication with the Arduino card, which allows to activate or deactivate the solid state relays C31 and manipulate the resistance level in the C28 potentiometer that change the intensity level of electrical stimulation. Additionally, the C29 potentiometers change the contraction and relaxation time for the stimulation process. To connect the digital potentiometers to the electrostimulation module 3-pin C24 connectors are used, for the activation of each stimulation channel 2 pin C23 connectors are used. The C30 optocouplers have been added for protecting the MCU Arduino board from currents derived from the activation of the C31 relays. The electronic devices included in this board are powered with 5V from the Arduino board through the C23 connector.

Electrostimulator: The electrostimulator device is modified, by removing the analog potentiometers on board, pins are used to connect the digital potentiometer that control the intensity of electrical stimulation and the digital potentiometer for setting the contraction and relaxation time in the stimulation process and the activation of the stimulation channels. This module is connected to the control card by means of cables according to the corresponding element. In Fig. 10a and 10b the connection points are observed, corresponding to the digital potentiometer and the On/Off relays.



(a) MCU training system control card connections.



(b) Power and regulation I/O board.

Fig. 9. Main electronic boards assembly, MCU interfaces and power-regulation I/O board.

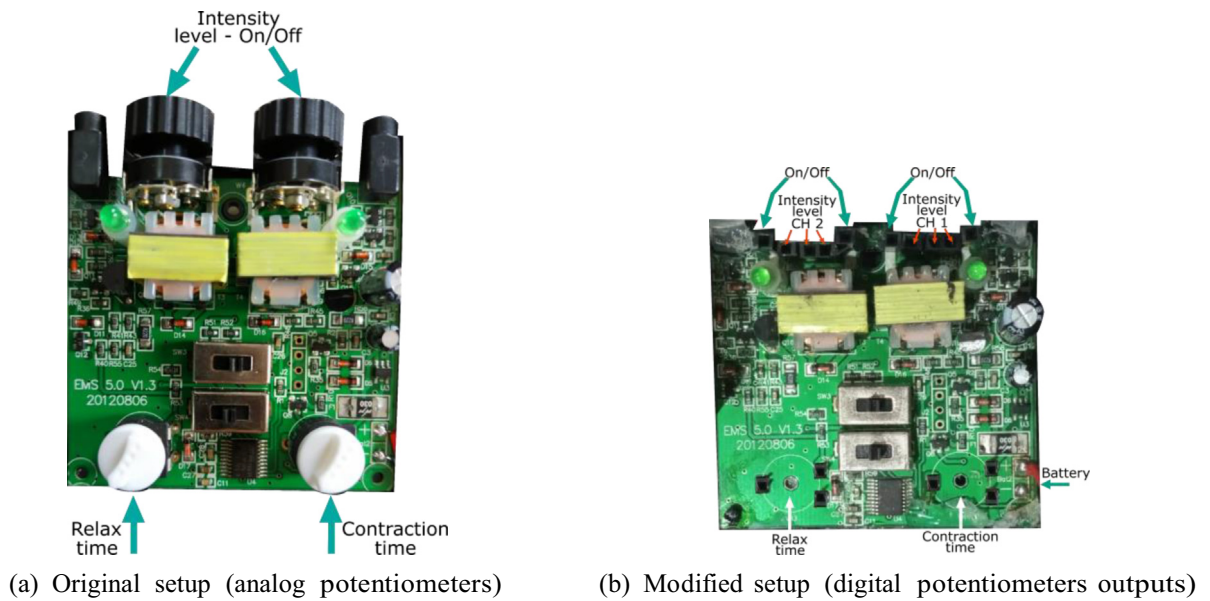


Fig. 10. Modifications made to the commercial electrostimulator, replacing analog potentiometers by digital MCU controlled counterpart.

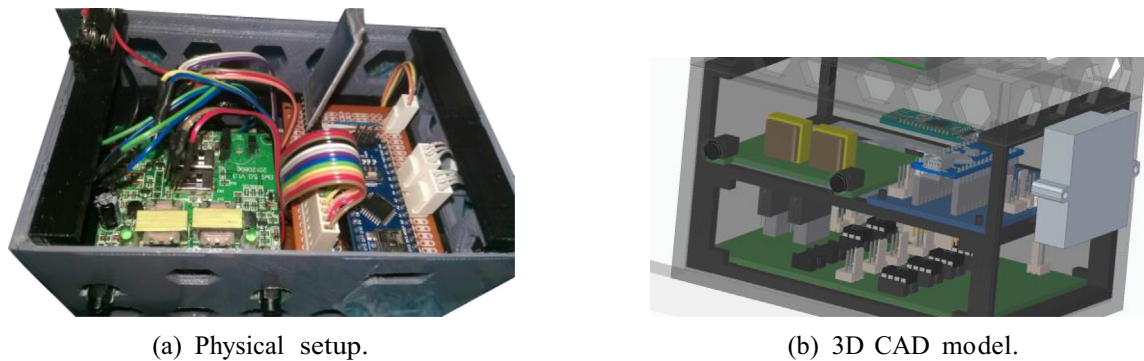


Fig. 11. Location and connection of the electronic system in the 3D printed cover.

Electronic assembly: Fig. 11 shows the distribution of the electronic modules that make up the training system; they are located in a 3D printed box that places the cards at different levels. This box allows securing the cards in such a way that the movement does not affect the devices that make up the electronic system. This box is secured to the cuboidal metal base of the training platform.

6. Operation instructions

Before operating the DorsixRehab system, it must be taken into account that electrostimulation is a process that must be applied carefully and the intensity level of the stimulation is different for each patient. That is why it is necessary to adjust the intensity levels according to the tolerance of each individual and it is mandatory to listen carefully to the information and any possible pain signals coming from the patient.

6.1. Rehabilitation protocol

Fig. 12 shows a flow diagram indicating the necessary steps to start the rehabilitation process and the DorsixRehab system.

Fig. 13 presents the software interfaces developed for DorsixRehab system. The IVR application is presented in Fig. 13a, as can be observed running in a low cost commercial smartphone (Xiaomi Note 5) and mounted in a low cost virtual reality

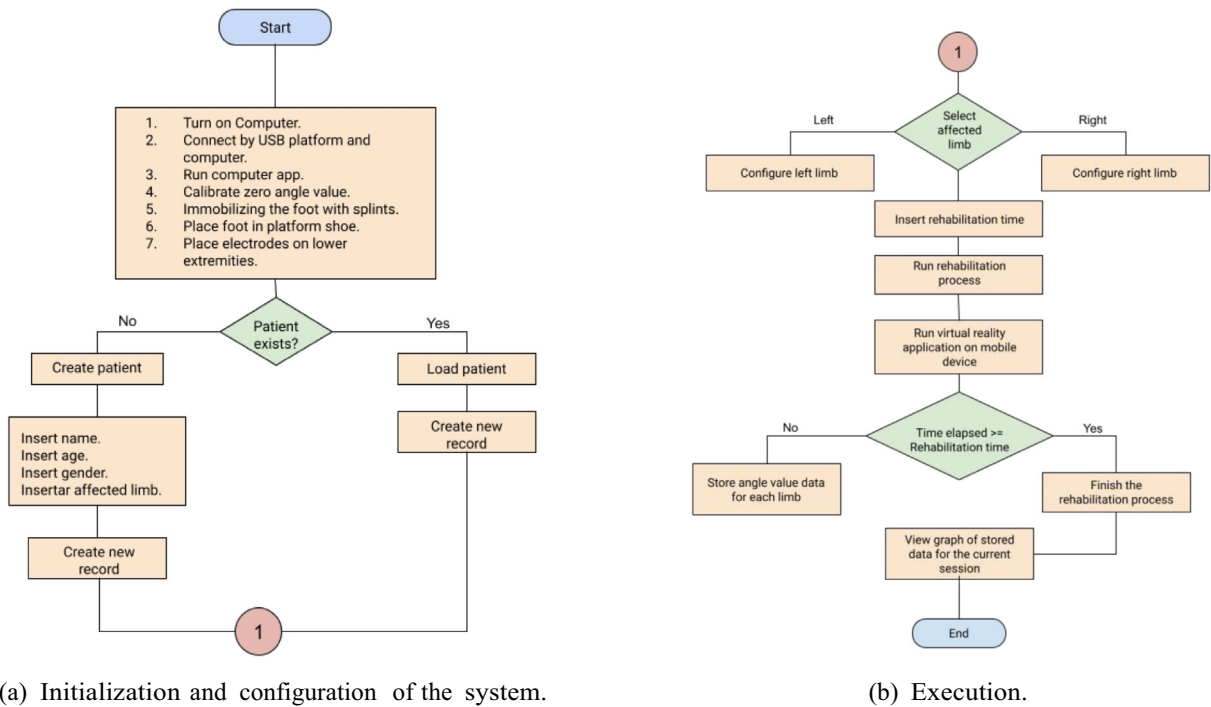


Fig. 12. Flow diagram for the setup and running of the DorsixRehab system.



(a) Virtual reality application running on a smartphone.



(b) Desktop software for control and real time analysis.

Fig. 13. Software interfaces of the DorsixRehab system, presenting the IVR application and the desktop software.

glasses (VRBox). In terms of minimum specifications, for the mobile device it is only required a smartphone with a complete IMU (accelerometer, gyro and compass) running Android 5.0 or superior, as well as the Bluetooth module.

The image observed in Fig. 13a corresponds to the information real-time seen by the patient, captured by the angular position sensors, processed by the MCU and then sent through Bluetooth interface to the smartphone, and then it is introduced into a home-like 3D environment. It should be noted that the information sent from position sensors is presented mirrored in the IVR application, this is, the IVR application implements the MT.

The same information showed by the IVR application, is also presented in the desktop application (Fig. 13b). This application allows the DorsixRehab system setup (see Fig. 12), real-time data plotting and saving for offline data postprocessing (see Fig. 16 for example). In terms of minimum specifications for the desktop computer it is only required a PC running Windows 7 or superior, 2 GB RAM memory and USB communications port.

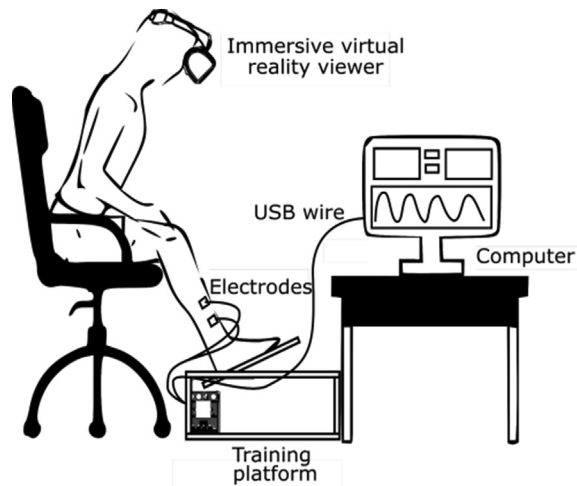


Fig. 14. Location and connection of the DorsixRehab system involving the patient.

6.2. Location of the elements

Fig. 14 shows the location of the elements necessary to carry out the training process for the recovery of the movement in the lower limbs, for this process a chair is needed that allows the person’s leg to be accommodated in the required position, this chair is not part of the training platform device. In the videos located in folder `.. Video` (Video) the operation of DorsixRehab system is observed and tested in a volunteer participant.

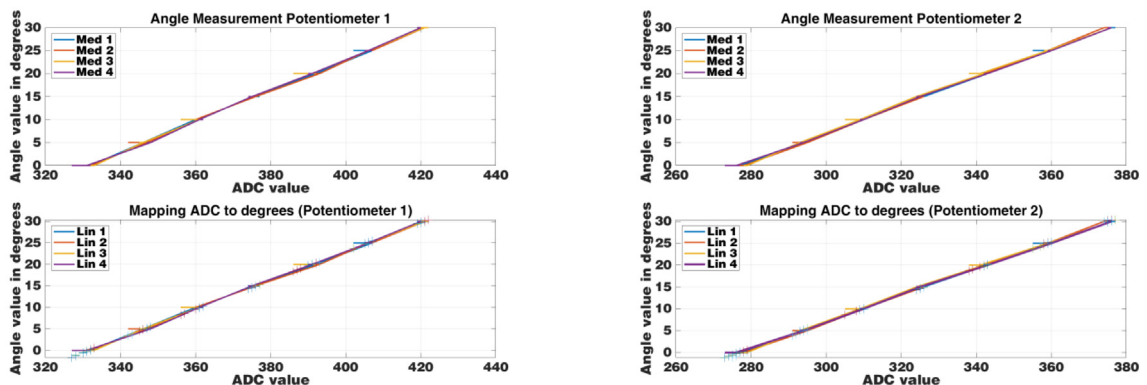
7. Validation and characterization

7.1. Sensor calibration

The sensor is located in the middle of the stem travel, as an initial point of reference the foot support base is placed in the horizontal position corresponding to an angular value equal to 0° (parallel to the cuboidal base), a protractor is located as a measurement reference which is centred in the pivot point of each bearing. In intervals of 5° , the position of the base is changed starting with an angle from 0° to 35° . The ADC of the Arduino Nano card captures the data corresponding to the angle measure for 1 min, the data is sent to the computer application which store the data in plain text files, this process is carried out 4 times for each angle measured in order to obtain the mean value of the measurements made.

A script developed in Matlab reads the files corresponding to the measured angles, performs the data analysis and obtains the straight-line equation that allows transforming the data obtained by the ADC to its corresponding angular value in degrees. Fig. 15 shows the graphs of the transformation process from digital values to degrees for each sensor.

A linear function is considered for data transformation, this is,



(a) Sensor 1.

(b) Sensor 2.

Fig. 15. Measurement and transformation of angle sensors.

$$y_i = p_{1i}z_i + p_{2i}, \quad i \in [1, 2], y_i \in [-30^\circ, 30^\circ], \tag{1}$$

where y_i is the calculated angular value, and p_{1i}, p_{2i} are the parameters of the first order polynomial. The slope of function (1) can be obtained by

$$z_i = \frac{x_i - \mu}{\sigma_i}, \tag{2}$$

where x_i is the measured digital analog value, μ_i is the measure of x_i and σ_i is the standard deviation of x_i . The term i refers to the location of the sensor used, where $i = 1$ correspond to the left sensor and $i = 2$ corresponds to the right one. The other parameters of (1) are summarized in Table 1. Each equation is entered in the firmware of the MCU to perform the real time conversion of angular values corresponding to the dorsiflexion movement.

7.2. Evaluation of the functionality of the training platform

The results obtained from the dorsiflexion process with one healthy volunteer are presented. The dorsiflexion in the both lower limbs was evaluated through the behaviour of the angular movement in relation with the electrostimulation process and IVR visualization. It should be noted that the DorsixRehab system has been designed to implement rehabilitation processes in people with reduced dorsiflexion mobility. However, since the scope of this work is to present the open hardware/software technology developed, a simple test has been carried out with a healthy person, with the main interest being the evaluation of the operation and behavior of the system. It is not the object of this test to analyze any result or effect in a rehabilitation process. A first case study was conducted in a post-stroke patient (see [1]).

Fig. 16 shows the dorsiflexion movement generated in the lower limbs during the training process. As said before, a healthy participant was considered for this evaluation, thus the maximum angular movements allowed by the platform were obtained by both lower limbs, as shown in Fig. 16. It is also observed that the frequency stimulation was similar in both limbs for contraction and relaxation.

In Fig. 16b the upper graph shows the dispersion of the maximum angles achieved by the right limb, it can be seen that the values are concentrated around 35° with a dispersion between 36° to 37.5° . For the left extremity corresponding to the lower graph, the angular motion data is concentrated around 33.9° with a range between 34.3° to 33.7° . The participant level of motor skills behaves within the normal ranges of motor functionality, the dispersion of the data shows a dispersion of two degrees, which indicates that the participant has control in the movement of the limb, since it reaches similar angular values. It should be noted that both plots depicted in Fig. 16 have been obtained offline from the data saved through the desktop application, included here for the sake of analysis and validation.

Table 1
Parameters of the polynomial for conversion from ADC values to degrees.

Sensor	σ	μ	p_1	p_2
Left	32.58	326.2	9.99	15
Right	29.72	376.18	9.99	15

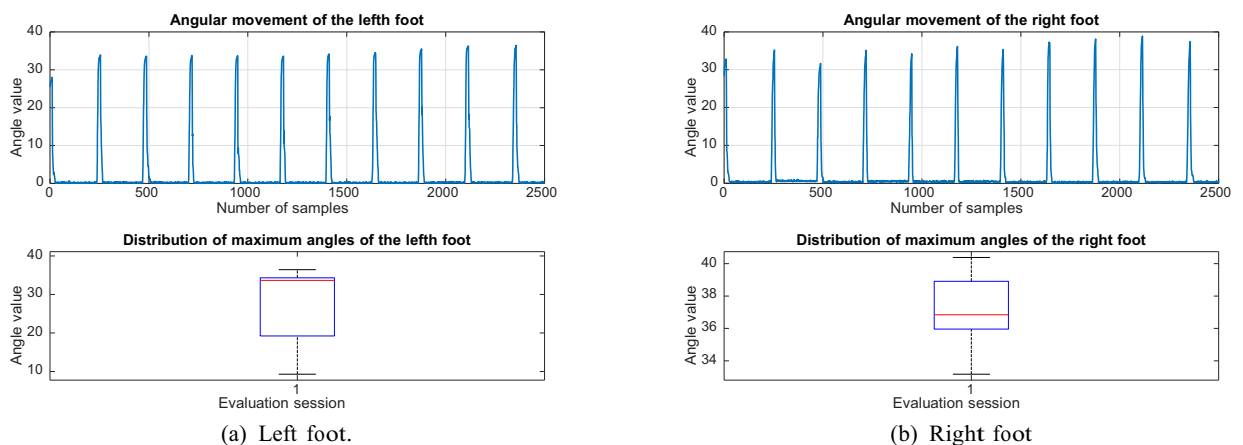


Fig. 16. Time responses and dispersion of the maximum angular values for a healthy person using the system.

Ethics statements

The experiments described in this work have been carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans. In addition, the participants gave their informed consent approved by the Ethics Committee of the Universidad del Cauca, Colombia.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.ohx.2022.e00285>.

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