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Test Results and Considerations for Design Improvements of L-CADEL v.3 Elbow-Assisting Device

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Abstract: The elbow-assisting device, L-CADEL, was analyzed by testing a prototype of design version three (v3) with the aim of discussing design improvements to solve problems and improve operational performance. The test results reported are from a lab testing campaign with 15 student volunteers from the engineering and physiotherapy disciplines. The main aspects of attention of the reported investigation are data analyses for motion diagnostics, comfort in wearing, operation efficiency, and the mechanical design of the arm platform and cable tensioning.

Keywords: motion assistance; elbow-assisting devices; prototypes; testing; design; L-CADEL

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1. Introduction

Diseases and age can lead to degeneration in the muscular control system and abnormal limb patterns [1,2]. This issue is common and has far-reaching effects, mainly among elderly people. It also affects patients with neurological disorders, those suffering from prolonged illnesses, or individuals who have experienced traumatic events [3–5]. There are other diseases that often affect the limb. They occur at birth, and they can affect movement and muscle tone or posture, especially in children. This includes cerebral palsy (CP) [6], spina bifida, muscular dystrophy, and spinal muscular atrophy (SMA). Some of these diseases cause damage to the developing immature brain or result from improper spinal cord formation. Genetic conditions can lead to muscle mass loss, weakness, and muscle wasting, also known as atrophy [7,8].

Rehabilitation through physical therapy and exercise programs, which often involve slow and repetitive exercises, has been proven as a good practice [9] that can help restore control, maintain body motor functions, manage symptoms, and improve mobility and muscle control [10]. Sometimes, this is achieved with the help of orthotic or assisting devices.

These exercises contribute to recovery, as noted in [11–13], by improving:

- Neuroplasticity: This is a case wherein repetitive exercises stimulate the brain to revamp itself to improve motor control and the brain's ability to reorganize itself by forming new neural connections.
- Muscle Strengthening and Conditioning: Muscle strength and endurance without causing injury can be regained by a gradual increase in the intensity and duration of exercise.
- Motion Learning and Skill Acquisition: Repeated practice of specific movements enhances motion learning so that exercise movements become more precise and controlled, leading to improved functional abilities.
- Joint Flexibility and Range of Motion: Repeated movements help to maintain and increase joint flexibility, preventing contractures and stiffness of muscles.
- Cardiovascular and Pulmonary Health: Improved cardiovascular and respiratory function can be experienced with a gradual increase in aerobic exercises, which support overall physical health, enhancing the body's ability to perform daily activities and reducing fatigue.

- Pain Management: Chronic pain and discomfort can be reduced by targeted exercises that improve circulation and release endorphins, making it easier for patients to engage in physical activity and therapy sessions.

In addition, motion-assisted activities provide psychological benefits since they enhance mood and reduce anxiety and depression and, in addition, they can enable balance, coordination, and functional independence.

Despite its benefits, physical therapy is often challenging, costly, and lengthy since it requires multiple sessions with predetermined exercise routines, even with nurse assistance. These aspects motivate research activity and developments in the fields of assistive technologies and robotic rehabilitative devices [14]. In general, assistance devices are conceived as substitutes or supporters for physiotherapists, and they can provide convenient care for individuals with limited mobility. The aims of these devices also include exercise for elderly people and rehabilitation of impaired body extremities by even reducing dependency on medical staff and delivering controlled repetitive training at a reasonable cost and time.

In the last decades, there have been many technological innovations geared towards the creation of assisting devices, with important areas and trends towards improving the quality of life for those with these needs. These assisting devices include fixed and mobile rehabilitation devices and robotic exoskeletons [15], even with cable-driven actuation [16–18]. Some of these devices are specifically developed to function in the upper or lower limbs [19].

The practice results show that repeated use of these devices largely guarantees the restoration of joint motion function [20]. If designed for home and daily use, these devices enable users to perform exercises autonomously, with little or no supervision from medical personnel or assistants. Therefore, the development of such assisting devices is significant in terms of practical therapies and exercises with cost reductions.

In order to be effective in rehabilitation and even for elderly people, attention is focused on the adaptability to various therapeutic needs through the customization of repeatable exercises that can be performed according to different control protocols, which include the following aspects:

- Exercise planning: This assists a user with afflicted limbs in moving in a predefined trajectory to straighten the limb muscles and rebuild the human motion control system.
- Motion control: This is a proper method to help patients follow a desired exercise trajectory while allowing for some deviation based on the impedance of human-like gain.
- Force planning: This operates by strengthening the muscles by providing resistance against movement by simulating everyday normal activities, even using tactile interfaces.
- Encouraging exercises: These are performed with planned actions to encourage patients to perform exercises.

Considering the achievements in technology and research towards developments in assistive technology, one could wonder why most of the devices so far developed are not popular in the market or not widely accepted. Studies indicate that several of these devices are so rigid that they cannot provide proper mobility and workspace; although the designs may seem appropriate to motion-assisting tasks, they do not really fulfill the requirements for a user-oriented-assisting operation. The main conditions for this can be indicated by the fact that an assisting device needs to be portable, inexpensive, and easily adjustable to different patients/users and for different needs by offering approaches, including for home exercises [21–23]. In addition, it is expected that a motion-assisting device should also effectively provide feedback to physiotherapists, such as by remote monitoring, data storage, and autocorrecting actions, to diminish errors during each exercise iteration [24], even with passive motion tracking [25].

Cable-driven-assisting devices represent an efficient solution for providing suitable, precise, and repeatable movements [26–29] to help partially or fully restore lost joint function since they can be lightweight with performance flexibility and distribute assisting forces more effectively [30].

The light cable-driven elbow device (L-CADEL v3) [31] represents a significant solution in elbow-assistive technology, following two previous versions. This assisting device highlights interesting aspects with improvements in performance and usability [32] by increasing autonomy and enhancing the capacity to guide all possible movements of the forearm relative to the arm, facilitating potential users' acceptance [33–35].

Following improvements for the last version, L-CADEL v2, L-CADEL v3 attempts to address previous limitations and incorporate user feedback to further improve the elbow-assisting capabilities. This paper presents the test results of a prototype of L-CADEL v3, focusing on the performance metrics, user experience, and areas for improvement. By analyzing the test results, we discuss the implemented design enhancements to propose further improvements for future device solutions. Therefore, in Section 2.1, we have presented the requirements and problems for elbow motion assistance, whereas Section 2.2 highlights and discusses the design of L-CADEL.v3, specifying the conceptual design through to the kinematic design as well as the prototyping of the device prototype. Section 2.3 introduces the testing layout and modes indicating data acquisition with post-processing. Section 3 presents the test results and their analysis for test data interpretations and considerations for future improvements.

This paper presents an extended version of the paper "Results and problems from lab testing with L-CADEL.v3", which was presented at the MEDER 2024 6th Symposium on Mechanism Design for Robotics, held in Timisoara (Romania) on 27–29 June 2024 [36].

2. Materials and Methods

In design problems, breaking down the task functions into sub-functions simplifies the process of finding solutions. The detailed flowchart of the requirements and problems for the device design and improvements is summarized in Figure 1.

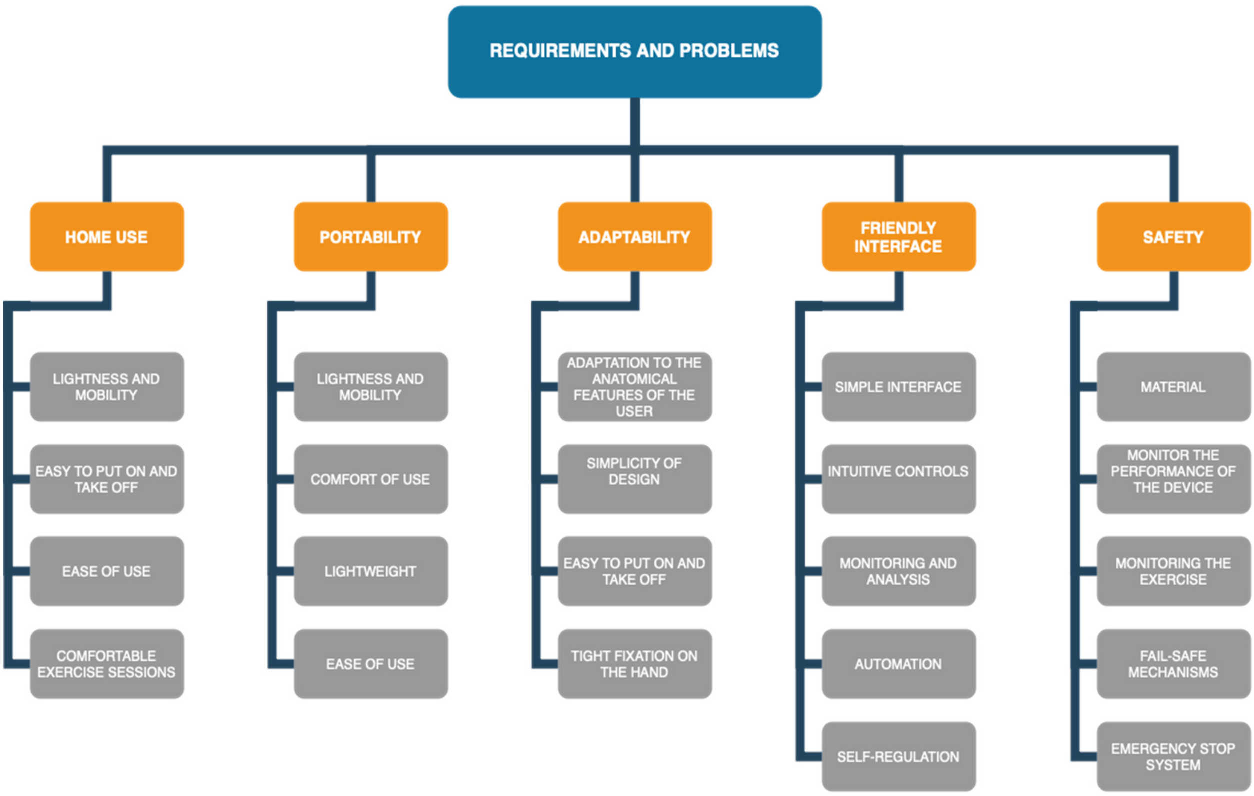


Figure 1. The main requirements for design issues in a motion-assisting device for the elbow.

2.1. Requirements and Problems

Motion-assisting devices can be effective in performing exercises by both elderly people and athletes and in rehabilitation therapies when restoring impaired motion functions. The main requirements and problems for developing an assisting device are summarized in Figure 1, in which specific aspects and related problems are split to identify the specific main requirements in elbow motion assistance:

- Home use. One of the goals is to develop an assisting device for home use. This type of device will allow a user to exercise daily or several times a day with little or no input from the physiotherapist or medical staff. This will speed up the recovery of elbow motion and allow the physiotherapist to concentrate on more complex cases. This target will require proper design features, ensuring the user-oriented capability to handle and operate such a device so that the main characteristics can be identified in a light, compact design, easy operation, and comfortable wearability.
- Portability. This design requirement is focused on developing an assisting device that is useful and convenient for all users. For comfortable and adaptable usage, a portable device should be lightweight and not exceed 1 kg. In addition, a device should contain only the necessary elements with simple and intuitive motion planning commands.
- Adaptability for users. Each user has unique anatomical features and characteristics such as age, weight, height, hand size, and muscle activity. An assisting device should be easily adaptable to any part of the anatomy of a user, allowing her/him to comfortably wear all elements of the device and fix them properly to ensure they perform the required exercises properly. In particular, an elbow-assisting device must be designed to be adaptive and easily and tightly fixed to the user's arm and forearm.
- Friendly interface. This will allow a user to conveniently, intuitively, and usefully use all the capabilities and functions of the device. It is desirable to have a simple operation interface that will have intuitive options. It is useful if the system also has a monitoring system and data analysis capability, with the possibility of providing the system with an intelligent reaction to make decisions during the operation. Self-regulation based on sensor data and user response will provide a suitable level of autonomous operation. The introduction of modern technologies and the ability to operate the device via a smartphone can provide additional advantages and ease of use.
- Safety. For this type of medical device, safety is one of the most important aspects. Each element of a device must be safe for the user with her/his awareness. This may include considerations on the materials with which the device is made and operation procedures with control equipment and a user interface. It is also necessary to monitor the movement of the hand and the user's condition during the exercise. For monitoring purposes, it is possible to use EMG sensors for muscle activity and IMU sensors for motion detection. Safety will also include emergency solutions both in hardware and software. In addition, linked to safety, disinfection issues can also be considered of primary importance when a motion-assisting device can be used by several users or even by a user in different periods and different conditions.

Main problems help to identify main requirements, as summarized in Figure 1, when considering them separately and then comprehensively so that they can indicate or require solutions in design and component selection for a specific motion-assisting device. Each of them can have an important influence not only in the design of a device but also in the choice of materials, control elements, sensors, data collection equipment, and analysis algorithms in specific solutions for an elbow-assisting device.

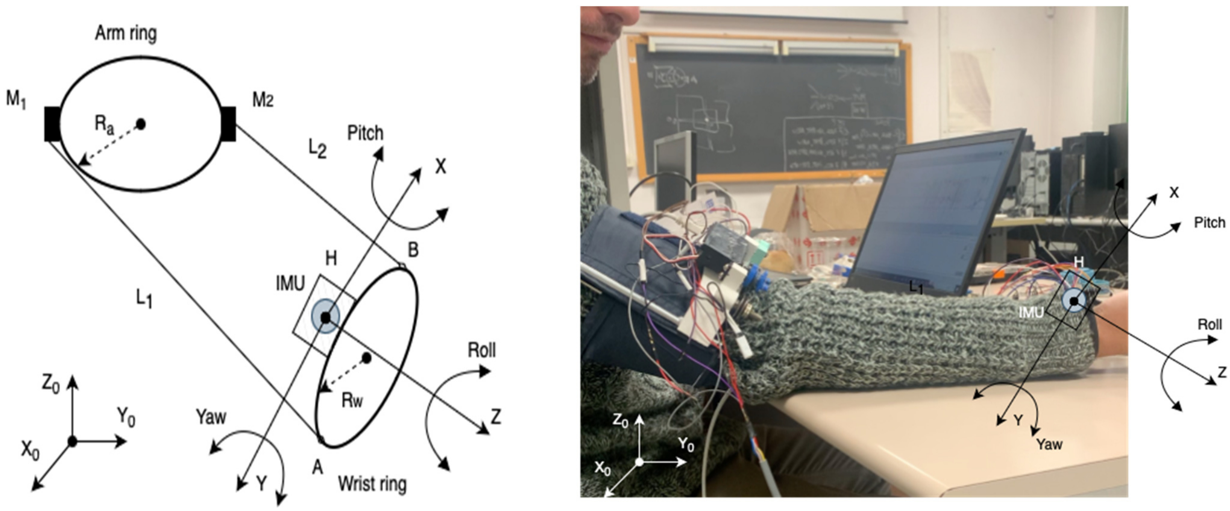
2.2. L-CADEL v.3 Design

The L-CADEL version 3 device was developed based on the above requirements in Figure 1. The prototype has two servomotors, a control system, and various sensors for feedback when operating the device during elbow movements to monitor the user's condition. The L-CADEL v.3 design has evolved from version 2, as reported in [21,30], in its design and operation aspects, such as in the design of the arm and wrist platform with a revised PLR ring frame and revised shape volume, cable guide system, control unit using an Arduino Nano on board, adding an Arduino Mega 2560 specifically dedicated to data acquisition and elaboration, codes in programming the servomotor operation, and sensor data acquisition during exercise.

The prototype as a motion-assisting device for elbow rehabilitation is designed for flexion/extension motion from 0 degrees to 140 degrees with the following components:

- Two servomotors of continuous rotation for raising and lowering the forearm;
- The Arduino Nano microcontroller for controlling servomotors;
- An IMU sensor for analyzing the forearm's movement in acceleration, orientation, and angular velocity;
- Current sensors to measure the power consumption by the servomotors;
- An EMG sensor to monitor the user's muscle activity;
- The Arduino Mega microcontroller for the acquisition and elaboration of data.

Figure 2a shows the conceptual design of the prototype. The arm ring is a platform that is attached to the user's arm. Ra is the radius of this platform. On the sides of the platform, there are two Parallax servomotors with continuous rotation, marked M1 and M2. The wrist ring is a platform that is attached to the user's wrist. Rb is the radius of this platform. Servomotors M1 and M2 run cables L1 and L2, which are attached to the wrist platform at points A and B, respectively. L1 and L2 move the wrist ring and the elbow joint moves with flexion/extension movement in the sagittal plane. An IMU sensor is installed on the ring platform of the wrist to measure the acceleration, orientation, and angular velocity of the induced movement. Figure 2 also shows the coordinate axes on the wrist ring with respect to which the angles pitch, roll, and yaw are measured.



(**a**) (**b**)

Figure 2. Design of L-CADEL v.3 prototype: (**a**) conceptual design and (**b**) prototype installed on a user's arm.

Figure 2b shows a prototype mounted on the arm of a volunteer user for testing. This picture was taken during one of the experimental tests at the LARM2 laboratory of the University of Tor Vergata. As shown in Figure 2b, the device platforms can be comfortably worn even on a user's clothing, demonstrating the comfort and flexibility of using the device for self-operation exercise.

Figure 3a shows the block diagram of the L-CADEL v.3 prototype with three platforms, including the third one for operation control and data elaboration. Each platform has its own elements for performing flexion/extension movements or elements for the acquisition and elaboration of data. The whole L-CADEL device consists of the following:

- Wrist ring platform (attached to the user's wrist);

- Arm ring platform (attached to the user's arm);
- A platform for the control unit, data acquisition, and elaboration.

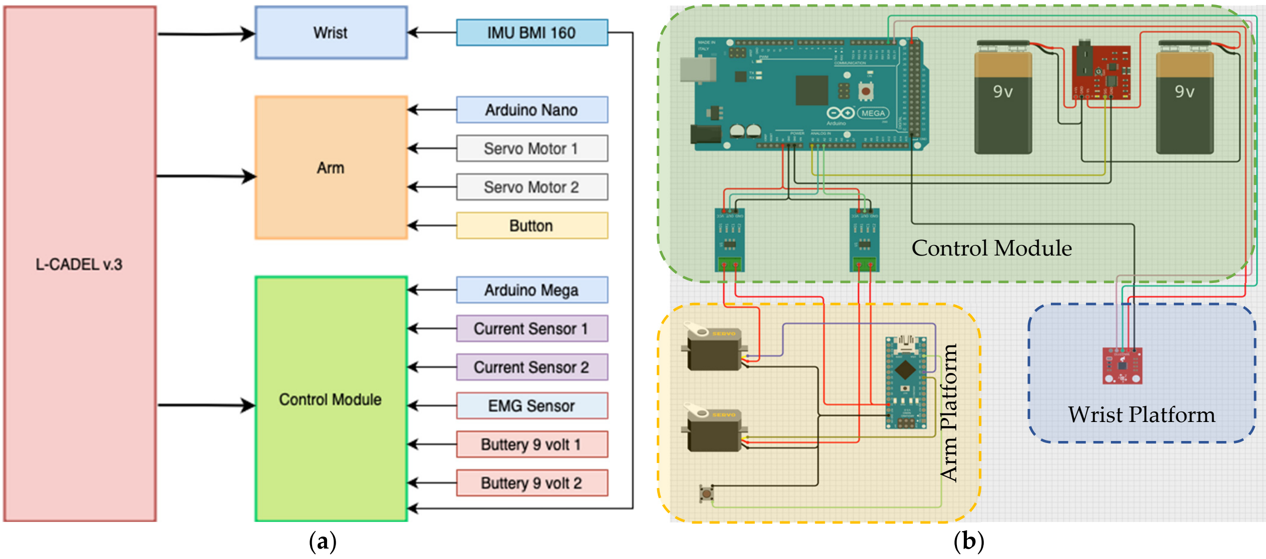


Figure 3. Design of L-CADEL v.3 prototype: (**a**) block diagram and (**b**) electric circuit design.

The upper platform, as the arm ring platform, is attached to the arm (biceps) near the shoulder. It represents a fixed platform that is tightly attached to the arm thanks to an inflatable band. The lower platform, the wrist ring platform, is attached to the wrist using a wrapping strip. Using cables actuated by servomotors, the device will move by raising and lowering the forearm and flexing/extending the elbow joint. The third platform, which has a servomotor control unit, is located on a table next to the user and also performs the function of collecting and analyzing data. This solution makes it possible to simplify the mechanical design of the device and to increase comfort when performing exercises by reducing the components and weight on the arm ring platform.

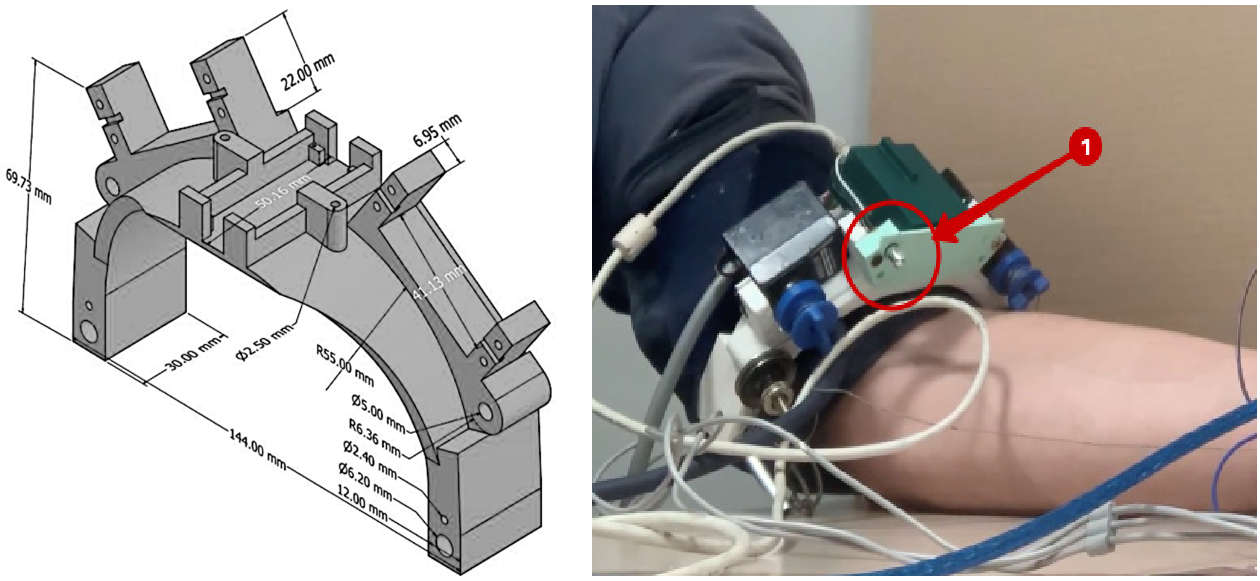
Figure 3b shows the electric circuit design of the L-CADEL v.3 device, referring to the control unit of the servomotors and the collection and analysis of data. The main functionality is provided by the Arduino Nano microcontroller to which two servomotors are connected through the digital pins D6 and D8.

Each servo motor has three wires as follows:

- The black ground wire connects to the GND on the Arduino Nano;
- The red power wire connects to the 5 V pin on the Arduino Nano;
- The yellow control wire is connected to either digital pin D6 or D8.

A button is connected to the digital pin D10 of the Arduino Nano to change the direction of rotation of the servomotors. The Arduino Nano is powered via a USB port, and the system works only when the microcontroller is connected to a laptop. In the electric circuit design, a microcontroller Arduino Mega is included to ensure correct data monitoring. Two current sensors, ACS 712, are connected to analog pins A1 and A2 to monitor the current consumption of the left and right servomotors, respectively. Each current sensor has three connections: the GND connects to the GND on the Arduino Mega and is responsible for grounding; the VCC connects to 5 V on the Arduino Mega and is responsible for power; and the OUTs are connected to analog pins A1 and A2, respectively, for transmitting the current consumption of the servomotors. An IMU sensor is connected to the SDA and SCL pins of the Arduino Mega to monitor wrist movement. Since the connection address is 0×68, the GND and the SAO are connected to the GND on the Arduino Mega and the VIN pin is connected to 5 V, respectively. The electric circuit design in Figure 3b also shows an EMG sensor for measuring muscle activity. Analog pin A0 on the Arduino Mega is used to transmit data. To power the EMG, two 9-volt batteries are used.

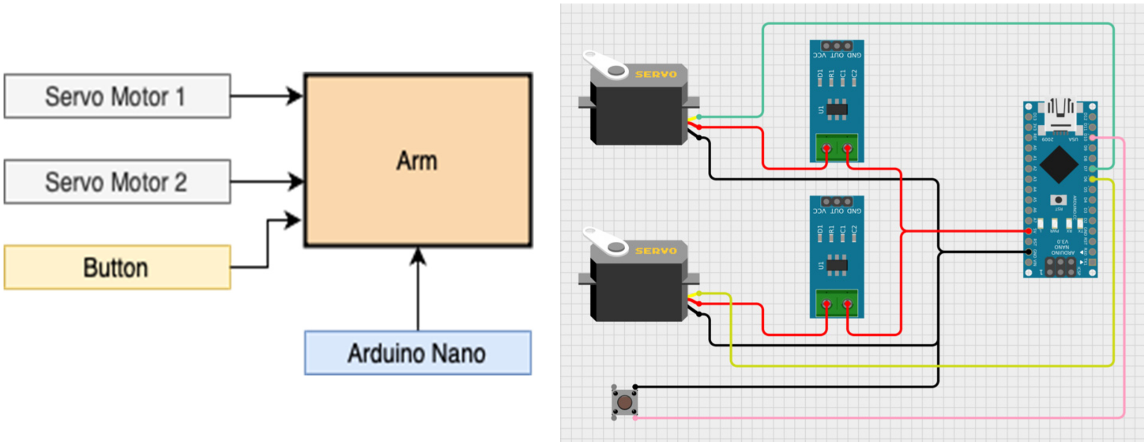
A new arm ring platform was developed with a plastic arc-shaped frame, shown in Figure 4a. This frame was printed on a 3D printer using PLA material with a length of 144 mm and a height of 85 mm. The plastic arc-shaped frame is the base frame on which the Arduino Nano microcontroller is fixed with four screws. Two constant rotation servomotors are installed on the sides of the arc-shaped frame. A button for changing the rotation of the servomotors is located above the microcontroller, indicated as number 1 in Figure 4b. Rings and cable tensioners are used for the correct winding of cables and raising the forearm. For each servomotor, there is a cable-tensioning system consisting of rings and pulleys. The pulleys guide the cables to ensure uniform tension and control of the cable winding during the elbow flexion movement. The ring arm frame is attached to the arm using a standard inflatable cuff. Thanks to the built-in pump and pump, the cuff can adapt to any anatomical features of the patient's arm. The plastic arc-shaped frame platform is attached to the inflatable cuff using metal pins and cables, creating a safe and secure human–machine mechanical interface with suitable comfort on the patient's arm. Figure 4b represents the arm ring platform installed on a user's arm.



(**a**) (**b**)

Figure 4. Arm ring platform of L-CADEL v.3 prototype: (**a**) a CAD model and (**b**) the built prototype installed on a user's arm. (1 is the button for changing the motor's rotation).

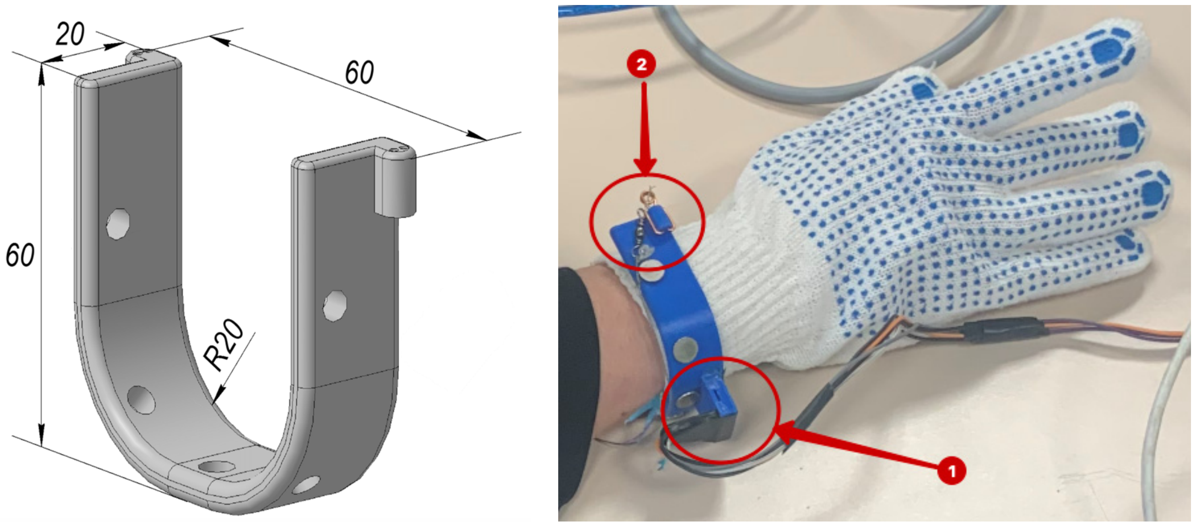
The conceptual design of the arm ring platform in Figure 5a includes two servomotors that are used to run the cables, providing rotational movement in flexion/extension of the forearm in the sagittal plane. For this purpose, standard servomotors #900-00005 of constant rotation are used. They are placed on the edges of the arc-shaped frame and are attached with screws. At the center of the plastic arc-shaped frame platform, an Arduino Nano microcontroller is installed to operate the servomotors that are connected to pins D6 and D8, respectively. The electric circuit design is shown in Figure 5b. The two ACS 712 current sensors shown in the electric circuit design are selected to monitor the power consumption of the servomotors. Their pins are connected to pins A1 and A2, respectively, of another microcontroller, Arduino Mega, which is located on the third platform for data analysis. The button in Figure 4b for changing the rotation of the servomotors is connected to the Arduino Nano at pin D10. At the initial position, the user's hand is on the table. When starting, the servomotors begin to raise the forearm, ensuring flexion of the elbow joint. When a flexion movement is made, and the wrist is in the highest position, the button is pressed to change the direction of rotation of the servomotors, permitting the extension of the elbow joint.



(**a**) (**b**)

Figure 5. Arm ring platform of L-CADEL v.3 prototype: (**a**) Conceptual design and (**b**) electric circuit design.

The wrist ring platform design is shown in Figure 6. It is an arc-shaped plastic frame of small size with a comfortable glove that easily automatically adapts to the anatomy of the user's hand. A CAD model of the plastic wrist frame is shown in Figure 6a. The model was printed on a 3D printer using PLA material. This frame is attached to the base of the glove using small screws that firmly and reliably fix the plastic frame to the glove. This design is convenient to put on and take off the wrist platform and quite tightly fix it on the wrist, providing an optimal position for performing flexion/extension movements. The arc-shaped plastic frame is optimally fixed on the user's wrist and allows for the precise tracking of wrist movement using the IMU sensor installed on it.

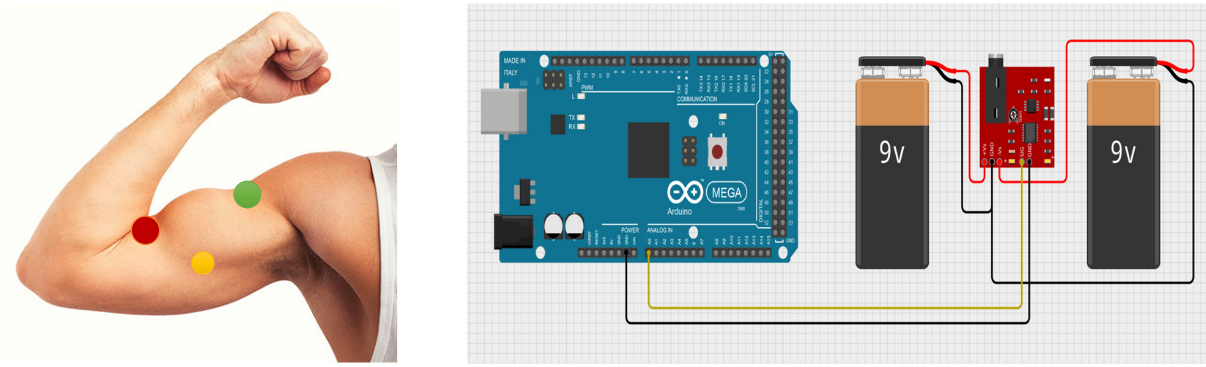


(**a**) (**b**)

Figure 6. Wrist ring platform of L-CADEL v.3 prototype: (**a**) a CAD model with sizes in mm and (**b**) the built prototype installed on a user's wrist. (1 is an IMU sensor; 2 is a cable connection hook).

Figure 6b represents the wrist ring platform installed on the wrist. At the base of the platform on the user's wrist, an IMU sensor, BMI 160, indicated as (1), is used for monitoring the wrist's movement in terms of acceleration, orientation, and angular velocity. The IMU connects to the SCL and SDA pins and transmits data to the Arduino Mega microcontroller, which is located on the third platform for data analysis. The GND and SDA pins of the EMG sensor are connected to the GND of the Arduino Mega with a power of 5 V from the microcontroller. Along the edges of the plastic frame, there are metal hooks, indicated as (2), that are used for fastening the cables coming from the ring arm platform.

An EMG sensor is used to measure the user's muscle activity, Figure 7a, whose electric circuit is shown in Figure 7b. It is powered by two 9-volt batteries. Power from the first battery is supplied to the +Vs pin, power from the second battery is supplied to the -Vs pin, and ground from both batteries is connected to the GND. The second GND of the EMG sensor is connected to the GND of the Arduino Mega, and the signal is connected to the analog pin A0. The Arduino Mega microcontroller is used for the acquisition and elaboration of data from the EMG sensor. Using Arduino IDE 2.0 software and post-processing in Microsoft Excel, it is possible to display the muscle activity data in a user-oriented form.



(**a**) (**b**)

Figure 7. EMG sensor of L-CADEL v.3 prototype: (**a**) EMG electrodes installed on the arm and (**b**) electric circuit design.

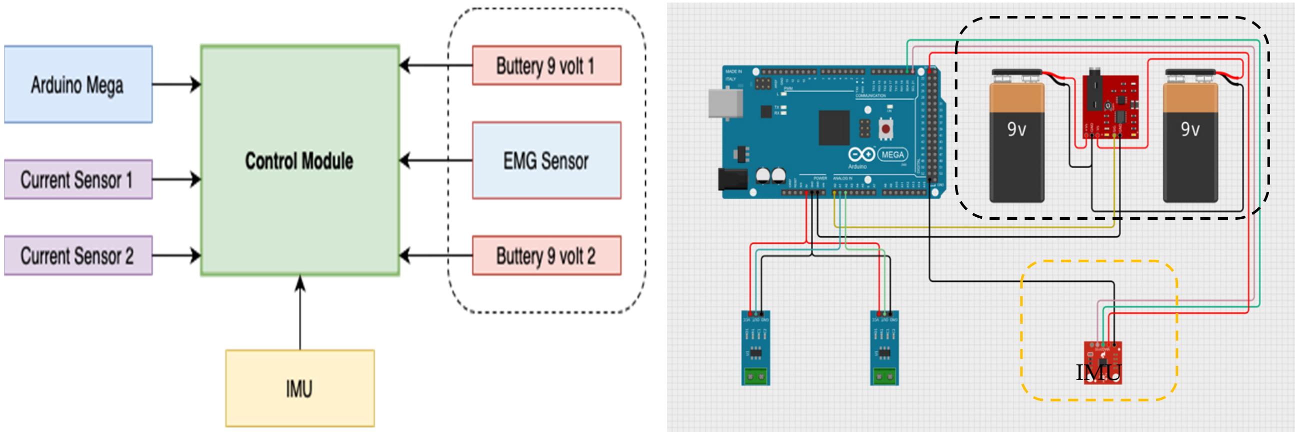
To obtain data on muscle activity, it is necessary to attach three electrodes (green, red, and yellow) to the muscles of the arm biceps that are responsible for the elbow motion. The diagram for attaching electrodes to the biceps is shown in Figure 7a. Red and green electrodes are attached to the ends of the muscle: the red one is on one edge close to the elbow, and the green one is on the other edge close to the shoulder. The yellow electrode is attached between the biceps and triceps. This arrangement of electrodes allows one to obtain fairly accurate data on muscle activity during elbow motion.

The conceptual design of the third platform with a control unit and data elaboration is shown in Figure 8a. The connection diagram is shown in Figure 8b. The basis of this platform is the Arduino Mega microcontroller in connection with the following components:

- Two ACS 712 current sensors are connected to analog pins A1 and A2 of the Arduino Mega. They acquire data to analyze the current consumption of the left and right servomotors running the cables.
- The IMU BMI 160 sensor is connected to the SDA and SCL pins of the Arduino Mega. This sensor is located on the wrist ring platform for measuring acceleration, orientation, and angular velocity during an exercise.
- The EMG sensor, which is connected to analog pin A0 of Arduino Mega, measures muscle activity during an exercise.

The Arduino Mega is powered via the USB port so that it only works when the microcontroller is connected to the laptop.

The two ring platforms and the control unit platform of the L-CADEL v.3 prototype are made from commercial components and plastic 3D-printed frames using PLA material. This construction solution makes the device prototype lightweight, functional, and compact with a user-oriented cost and operation.

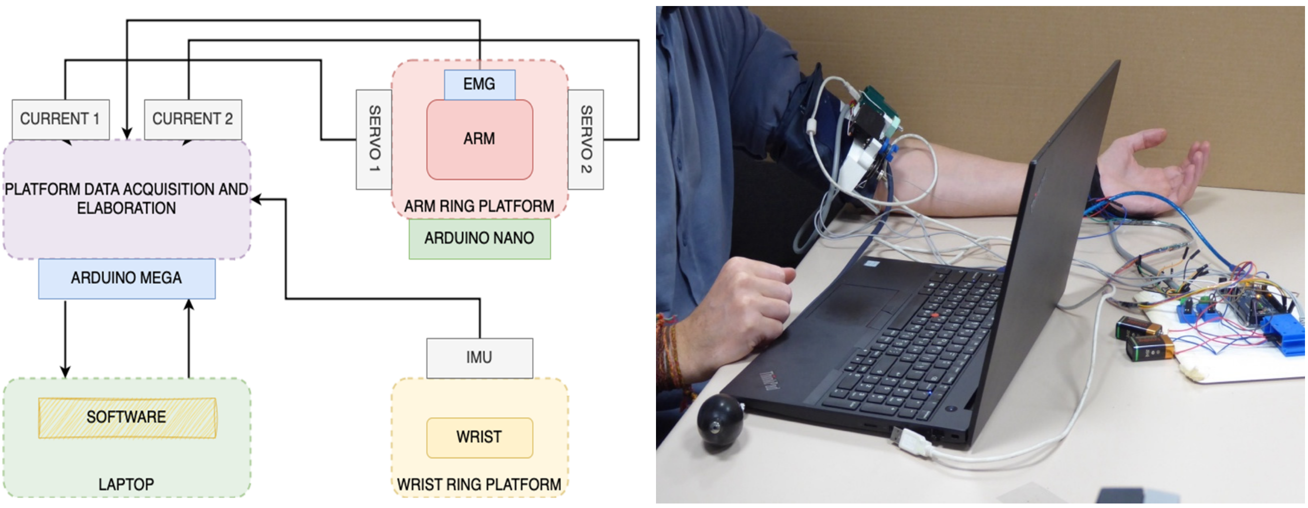


(**a**) (**b**)

Figure 8. The third platform for control unit and acquisition and elaboration data of L-CADEL v.3 prototype: (**a**) block diagram and (**b**) electric circuit design.

2.3. Testing Layout and Models

Laboratory experiments were carried out at the LARM2 laboratory of the University of Rome Tor Vergata. The purpose of the experiments was to test the performance and efficiency of the L-CADEL v.3 device. The conceptual design of the testing layout is shown in Figure 9a with the three platforms, namely the arm ring, wrist ring, and control and data unit. The wrist ring platform includes a wrist glove and a BMI160 IMU sensor. The user's forearm movement data are directly transmitted to the data acquisition and processing platform. The arm ring platform includes an inflatable cuff, an AD8232 EMG on the user's bicep using three electrodes, the plastic arc-shaped platform with two servomotors Parallax Standard #900-00005, an Arduino Nano microcontroller, and a button for changing the servomotor's rotation. The control and data elaboration platform includes an Arduino Mega microcontroller, two ACS 712 current sensors, and a micro-SD for data storage.



(**a**) (**b**)

Figure 9. Testing layout with L-CADEL v.3 prototype: (**a**) conceptual design and (**b**) a lab setup.

Figure 9b shows a laboratory setup consisting of the three platforms in operation during a test. The arm ring platform is attached to the user's arm; the wrist ring platform is worn on the user's wrist; and the control and data elaboration platform is located on the right side of the picture behind the laptop. The testing layout is also equipped with a laptop that performs two functions: it is a power supply for the Arduino Nano and Arduino

Mega microcontrollers via a USB port and is used to control the prototype and monitor the acquired data in real time. The Arduino IDE is used as data monitoring software.

The main characteristics of the L-CADEL v.3 prototype in the testing layout are listed in Table 1.

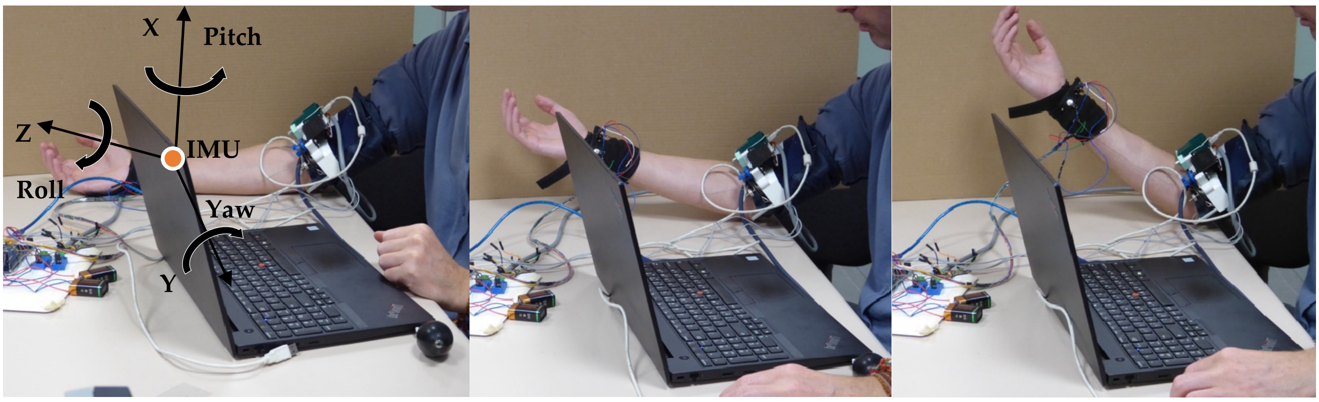
Table 1. The main characteristics of the L-CADEL v.3 prototype for testing.

Characteristics	Value
Weight (kg)	0.8
Number of platforms	3
Numbers of cables	2
Number of actuators	2
Number of microcontrollers	2
Sensors	EMG, IMU, Current

3. Results

The assisting device for elbow rehabilitation, the L-CADEL v.3, was tested in experimental trials with a campaign of repeated tests with 15 volunteers at the LARM2 Laboratory of the University of Rome Tor Vergata. The 15 volunteers were healthy students aged 22 to 40 years and included 4 women and 11 men in the first set of testing campaigns; more are planned for the near future with a larger number of participants for proper statistical significance according to the approved protocol for ethical authorization.

The test conditions are shown in Figure 10, following a properly designed protocol of the test plan with consensus given by the involved volunteers. The experiment in the example in Figure 10 is carried out by a volunteer while sitting on a chair. The hand on which the device is attached lies on a nearby table. The volunteer (40 years old, height 1.88 m) performed three cycles of an exercise that included flexion–extension of the elbow without load.



(**a**) (**b**) (**c**)

Figure 10. A snapshot of a test with the L-CADEL.v3 prototype setup. (**a**) Starting configuration; (**b**) intermediate configuiration; (**c**) final arm flexed configuration.

When the Arduino Nano is connected to a laptop, the device receives the necessary power and immediately starts working. It means that both servomotors automatically begin to rotate and raise the user's forearm. The speed is about 10 s/cycle. Figure 10a shows the initial position of a user testing this, Figure 10b shows the hand position during the experiment, and Figure 10c shows the final position of the raised forearm during the assisted exercises. Next, by pressing the button, the rotation of the servomotors changes, and the cycle is completed. The forearm makes the movement of extension of the elbow joint along the same trajectory. Comments on satisfactory comfort and ease of use were expressed by the volunteers, although some aspects were still detected to be lacking, as commented on later. Through the use of sensors, data are acquired as related to the performance of the system and the user's condition. Subsequently, those data are stored for post-processing and evaluation, including by medical staff.

Figures 11–14 show the acquired data during a test like that seen in Figure 10. The analysis of the data was carried out using visualization of Excel files for a user-oriented usage of the data for user post-processing.

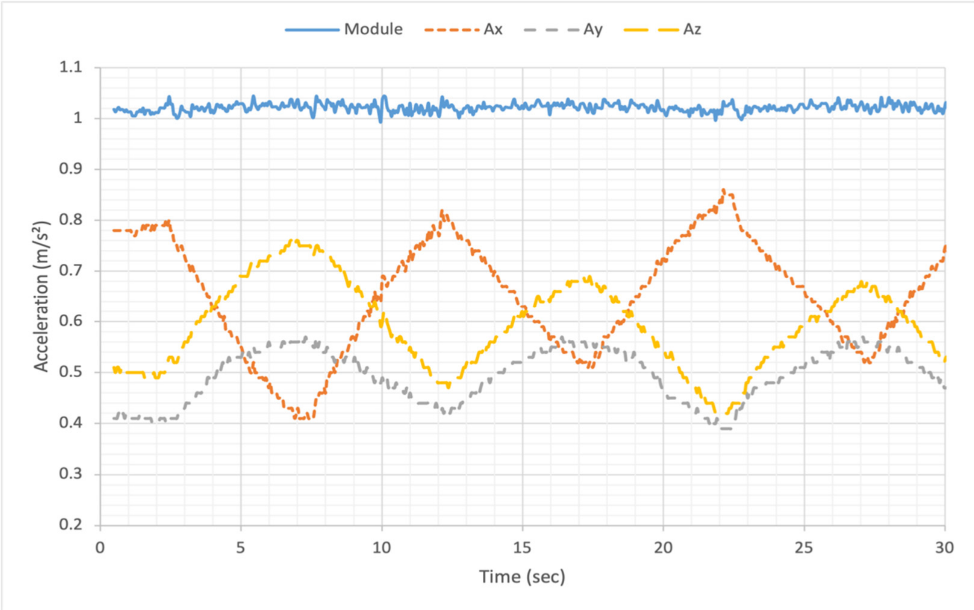


Figure 11. Acquired data during a test with L-CADEL.v3 prototype, as in Figure 10, in terms of the acceleration components Ax, Ay, Az, and module.

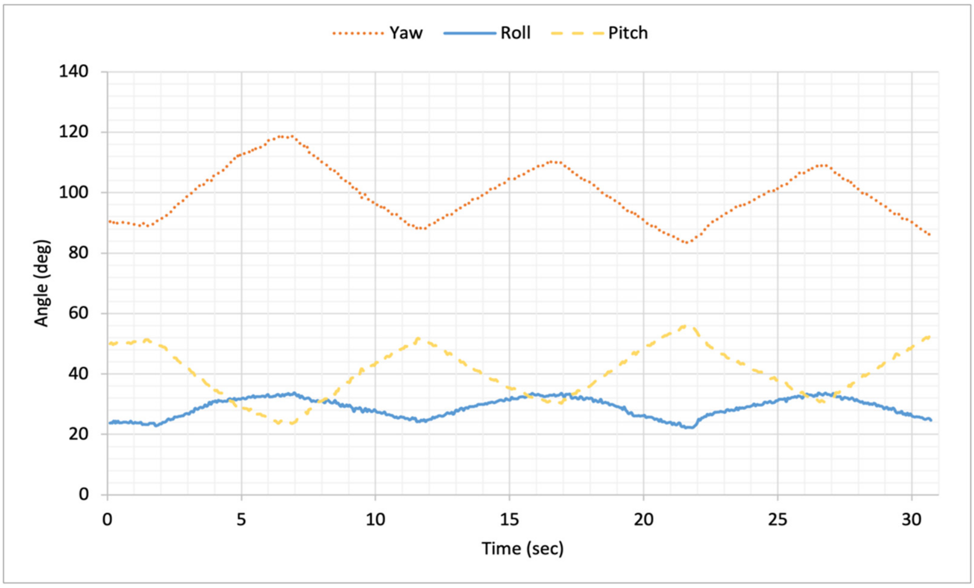


Figure 12. Acquired data during a test with L-CADEL.v3 prototype, as in Figure 10, in terms of the pitch, roll, and yaw angles.

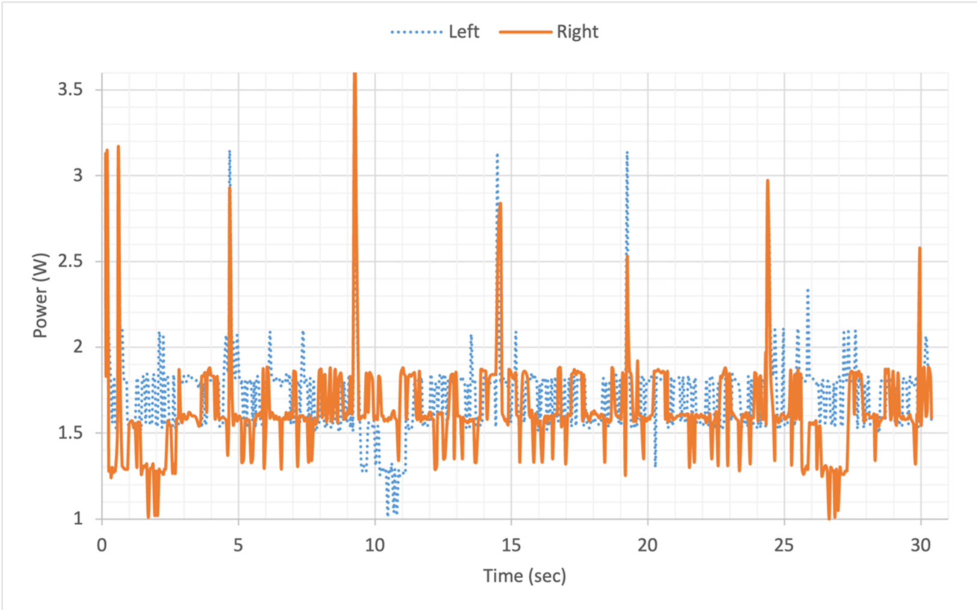


Figure 13. Acquired data during a test with L-CADEL.v3 prototype, as in Figure 10, in terms of power consumption.

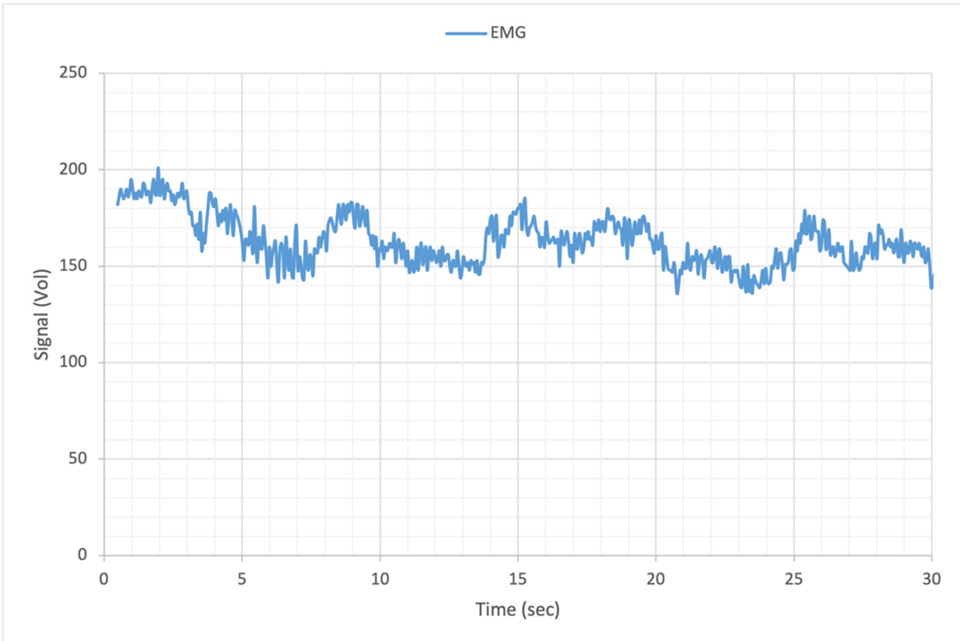


Figure 14. Acquired data during a test with L-CADEL.v3 prototype, as in Figure 10, in terms of the EMG response.

Figure 11 shows the acceleration data from the IMU sensor in terms of three components: Ax, Ay and Az, and the magnitude. Ax represents the acceleration in the sagittal plane in the horizontal direction, with values ranging from −0.32 g to 0.98 g. The time evolution shows slight decelerations and accelerations, with values corresponding to the cyclic movement during the exercise well in the sagittal plane. Az represents the acceleration in the sagittal plane in a vertical direction, with values ranging from 0.42 g to 0.78 g. These values correspond to the cyclic movement during flexion/extension of the forearm and indicate periodic changes in the vertical movement of the device. The components Ax and Az show expected values and characteristics. These acceleration data correctly represent elbow flexion/extension motions, which correspond to smooth cyclic motion in the sagittal plane in the vertical and horizontal directions. The ay horizontal component is orthogonal to the sagittal plane, whose values are detected as almost constant values with minimal changes, as expected for a movement only in the sagittal plane. However, in this case, the Ay values range from 0.39 g to 0.58 g, indicating occasional slight side-to-side wrist movement or lateral oscillation of the device while the user performs the exercise. In Figure 11, it is also possible to note that the axial components Ax, Ay, and Az are detected with a small noise, which may be clearly indicated in the small oscillations in the magnitude values. This may be the result of a slight tremor in the user's hand or that the user is tired and needs to rest. It could also indicate some anomaly in the anatomy of the user's hand or errors in the servomotors or cable tensions due to the connections.

Figure 12 shows the acquired angles. The pitch and yaw angles are detected with values that correspond to the movement of the forearm in the sagittal plane. The pitch angle values range from 23.45 deg to 58.89 deg. The yaw angle values range from 84.36 deg to 119.23 deg. Very small noise in the detected values may also be caused by tremors, fatigue, or cable tension errors. When performing the exercise, movement should occur only in the sagittal plane, and the roll angles should be zero. But, due to the characteristics of the human hand and anatomy, different values of the roll angles (from 21.20 deg to 36.56 deg) are observed, which indicates a slight movement of the user's forearm from side to side. However, it can be concluded that the values of all angles in Figure 12 well represent the smooth and efficient operation of the device throughout all three cycles of the exercise. It is to be noted that the noise in the angles is better reflected in the acceleration-acquired data, while the angle time evolution well monitors the angular movement of the forearm as related to the elbow motion. Those angle characteristics are detected with good, repeated values and behavior as related to the healthy conditions of the tested volunteer. The noise, both in the angle and acceleration values, can also be due to the slight motion of the arm and wrist platforms on the clothes, which are comfortable to wear with no very tight fixation.

Figure 13 shows the acquired values from the two ACS712 current sensors monitoring the two Parallax Standard servomotors, powered with a current of about 0.3 A. One current sensor is designed to measure the activity of the left servomotor and, accordingly, the second one for the right servomotor. The two servomotors' cycles can be recognized in about 10 s. The values of the current sensors during the raising or lowering of the forearm vary from 1.2 W to 1.8 W, with almost the same values in the two phases, indicating similar activity of the servomotors during flexion and extension of the elbow joint. Spikes of value occurring every 5 s indicate a change in the rotation of the servomotors. Typically, these peak values vary from 2.5 W to 3.8 W, although the expected values of the spikes should be approximately equal. This may be due to the fact that when performing the exercise, the arm ring platform may move slightly due to the platform not being tightly fastened to the arm, and the tension of the cables may become different. This can also be caused by the movement of the forearm from side to side. Thus, neglecting the spikes when changing rotation, the time evolution in Figure 13 represents minimal differences between the two servomotors when raising or lowering the arm. This indicates a smooth, regular operation of the servomotors working in parallel.

Figure 14 shows the data from the EMG sensor AD 8332 measuring the user's bicep muscle activity while performing an exercise. The acquired data show almost constant muscle activity, which indicates that the user's arm muscles are quite active and take part in the exercise. During three repetitions of arm flexion/extension, similar results are obtained with the time evolution characterized by the fact that when raising the forearm, muscle activity decreases, and when lowering the forearm, muscle activity increases. No large spikes were detected, as reported, in the plot, which indicates smooth muscle activity without sudden muscle tension and suitable motion assistance during the prototype operation.

Table 2 summarizes the maximum and minimum values of the sensors used in the L-CADEL.v3 prototype during the test with the data results in Figures 11–14.

Table 2. Maximum and minimum test values with L-CADEL.v3 prototype from Figures 11–14.

Components	Values
Ax (m/s^2)	0.41; 0.86
Ay (m/s^2)	0.39; 0.58
Az (m/s^2)	0.42; 0.78
Module (m/s^2)	0.98; 1.06
Pitch (deg)	23.45; 58.89
Roll (deg)	21.20; 36.56
Yaw (deg)	84.36; 119.23
Power Left Servomotor (W)	1.01; 3.16
Power Right Servomotor (W)	1.00; 3.89
EMG (Volt)	136; 203

The reported test data from the experimental tests at the LARM2 laboratory show that the L-CADEL v.3 prototype works well as being a lightweight, efficient motion-assisting device for the elbow. Due to the fact that the system and microcontrollers are powered by a laptop, the device can be used for a long period of time.

4. Discussion

The L-CADEL.v3 device prototype was proved to be a suitable, efficient device for elbow motion-assisted exercises thanks to its user-oriented design and operation matching the main requirements for motion assistance in home comfort usage with monitoring of assisted movements. Based on two cables operating in parallel, the movement of the user's forearm in the sagittal plane is ensured by the flexion/extension of the elbow joint. Considering the reported test results and the tested volunteer feedback, room for improvement can be identified to increase the operation performance in terms of comfort, exercise results, monitoring, and platform designs.

From a comfort viewpoint, the wrist ring platform can be improved by making it more compliant and adaptable to the user's wrist anatomy, possibly without the use of PLA material, while achieving a better fixture. Adaptation to the user's anatomical features and the ability to use them on the user's clothing will provide additional advantages in comfort and ease of usage towards better acceptance. An arm ring platform can be made similarly with a better design so as to be more adaptable and compliant to the arm's anatomy while ensuring a firm fixture. The device's efficiency can be improved by equipping the arm ring platform with the essential components necessary for controlling the device and, at the same time, performing the acquisition and elaboration of data. This will further reduce the number of platforms and make the device more portable and comfortable to use. Figure 15 summarizes the aspects that can be considered in redesigning the structure and operation of the device towards improvements, as suggested by the test results and volunteer feedback. In particular, Figure 15a shows a conceptual design for the arm ring platform with points of attention, and Figure 15b shows a platform for the wrist ring platform, with a source of attention for a new version of the L-CADEL v.3.

The following considerations address our attention to the main aspects of the design structure and operation features of the arm and wrist platforms, as well as to the complete elbow-motion-assisting device.

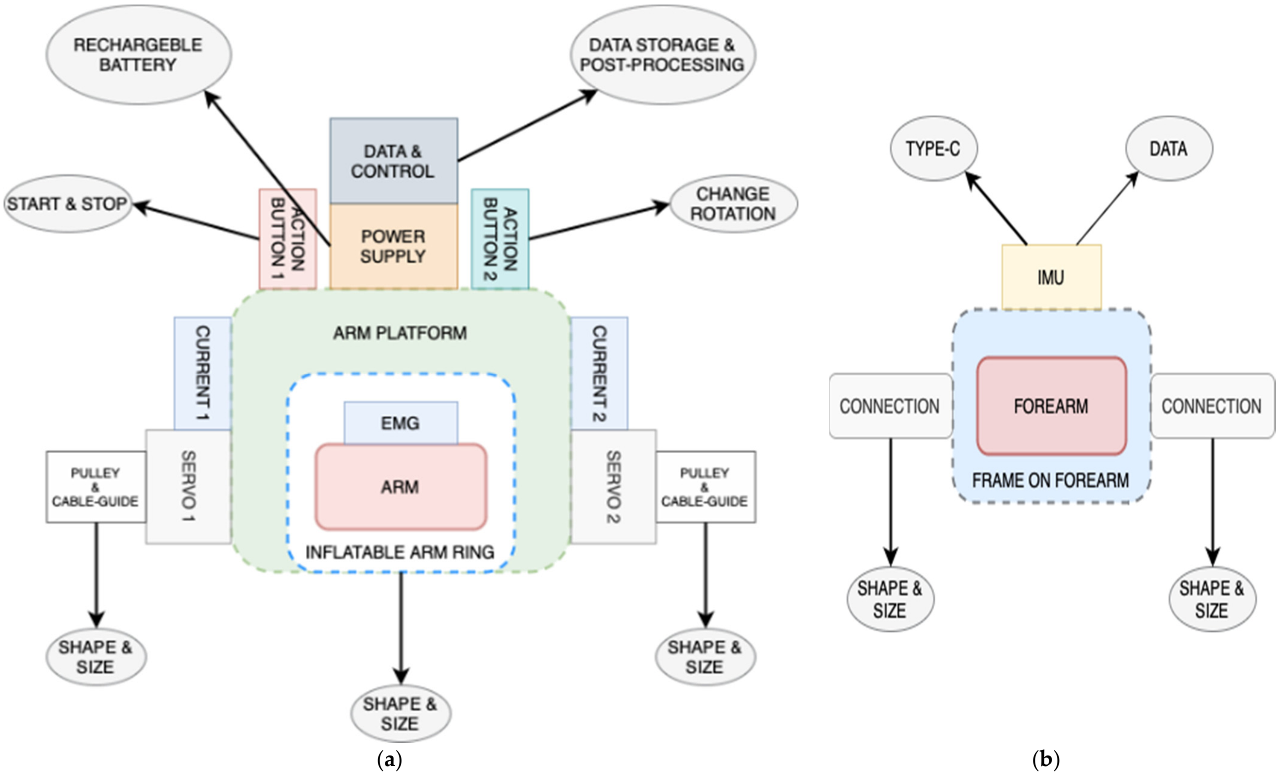


Figure 15. Schemes with aspects of attention for a new L-CADEL v.4 prototype: (**a**) arm ring platform and (**b**) wrist ring platform.

4.1. Considerations for Design Improvement

Referring to Figure 15, the main considerations for design improvement of the L-CADEL v.3 device can be identified as follows:

- Using only one Arduino Nano microcontroller will reduce the need for a third platform, and suitable additional software can also provide the possibility of elaborating acquired motion data for an intelligent operation against malfunctioning and/or wrong user actions.
- Replacing the bottoms for a start–stop of servomotor action with a code for controlled operation using the IMU data makes it possible to invert the servomotor rotation at the end of flexion and extension.
- A power supply with an onboard rechargeable standard battery will make the device more compact (without connection to a laptop) and more user-oriented, with no need for additional laptop equipment.
- A micro-SD module will make it possible to save convenient data for post-processing and make it available for medical supervisor staff to check the correct exercise running and consequent motion improvements.
- The fixture of the arm ring platform should be improved in static configuration and comfort, although the inflatable cuff has been recognized as being very suitable for self-user operation and adaptation; this may require investigating better configurations and even alternative structure solutions.
- The current device performs only flexion of the arm, and for extension back motion of the forearm, it depends on gravity and the arm user's capability for extension back motion of the forearm, so it is suggested to have a mechanism or an actuation that also performs assisted extension motion.
- A flexible strip potentiometer should be included to facilitate adaptability and adjustment of the cable lengths and runs for various users with different arm lengths.

- The cable guides with pulleys should be revised in size and topology for better tension regulation and maintenance during exercise for both phases of flexion and extension.
- The cable connections in the wrist ring platform can be reshaped and resized for easier cable insertion and efficient location.

4.2. Considerations for Operation Improvement

Referring to Figure 15, the main considerations for operation improvement of the L-CADEL v.3 device can be identified as follows:

- Using only one Arduino Nano microcontroller will facilitate and improve the efficiency of the programming for reading and collecting data from the sensors in real time, thereby improving the feedback capability, even during exercises, as a reference input, both for the user and medical staff.
- Motion assistance, also in the phase of extension, is required to complete the assistance of the full exercise by adding proper mechanisms and actuation.
- The process of inflating the arm wrap cuff should be automated to reach the pressure of air suitable for the fixture but convenient and safe for the arm conditions, and also in accordance with regulation and safety standards so that a user can easily and independently wear the device.
- The arm ring surface area needs to be increased to reduce the wrap pressure on the arm skin, following users' complaints related to discomfort due to the elevated pressure needs for a proper platform fixture.
- The location of the EMG electrodes on the arm biceps felt uncomfortable, and it was suggested to use a different configuration, perhaps on the arm triceps, so that when the arm is at rest or during an inflexion phase, the electrodes do not contact the arm ring platform.
- Data elaboration for user-oriented readability can be improved in terms of the interpretation of the effects of the exercise so as to provide satisfaction or an indication of correction to a user during the same exercise session.
- Data post-processing for medical use should be conveniently worked out to provide significant data for medical diagnostics, such as averages and data ranges, representative data-time segments, and even average plots with proper norms from repeated acquisitions.
- The fusion of acquired data from sensors will be conveniently elaborated to provide a better view of the interpretation of the monitoring and effect of the exercise, both for correcting and updating exercise running and motion diagnostics.

The testing campaign has been useful in checking and characterizing the feasibility and performance of the L-CADEL v.3 prototype as already suitable for physiotherapist applications. At the same time, thanks to interactions from the volunteers and physiotherapist collaborators, several of the above aspects have been seen as worthy of new attention for further development of the design and operation of an improved L-CADEL elbow-motion-assisting device.

5. Conclusions

The presented prototype L-CADEL v.3 is designed to restore and exercise the motion function of the elbow joint in the sagittal plane. The prototype was developed at the LARM2 laboratory of the University of Rome Tor Vergata.

Laboratory experiments were used to test usability and functionality, as well as to identify any open issues for further improvement. The experimental results at LARM 2 successfully show the potential and effectiveness of the device L-CADEL v.3 as suitable for performing assisted motion elbow exercises in a laboratory environment, resulting in an easy-to-use and portable device matching the expected goals. Its functional design and operational adaptability make it a promising device that can help people restore and assist elbow motion in exercise, both for rehabilitation and for the elderly exercising in home environments. The mechanical design of the arm and wrist platforms is suitable for all types of users since they are well-adaptable to the anatomy of different users. User-oriented operation capability allows for repeatable exercise sessions without the presence of a physiotherapist, with the possibility of telemonitoring thanks to the implemented sensors. The design of L-CADEL v.3 is mainly composed of 3D-printed PLA parts so that the total weight of the prototype is 0.8 kg, which makes it easy to transport and use the device in everyday life for comfortable exercises, both at home and in medical centers. In addition, the implemented sensors guarantee user safety when using the device since the EMG sensor provides control and monitoring of the user's muscle activity; the current sensors provide the monitoring activity of servomotors' power consumption; and the IMU sensors provide control and monitoring of the user's elbow motion during exercises. The overall cost of building the L-CADEL v.3 prototype does not exceed 30 euros.

The discussed laboratory experiments confirm the feasibility of the device with proper characterization, which can be used successfully in medical diagnostics and therapy activities, as well as for both rehabilitation and exercise for the elderly. However, after analyzing the experiment results and feedback from the tested volunteers, open issues were identified that will require improving the design and operation of the device with identified problems and suggested solutions in aspects related both to the structure's design and operation features. These improvements and adjustments will make the device more compact, convenient, and better portable so that a new design will allow users to use the elbow-assisting device for more comfortable and efficient exercises.

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