ROBMMOR: An experimental robotic manipulator for motor rehabilitation of knee

G. A. Navarrete[1], Y. R. Baca[2] , D. Villanueva[2-3], H. Estrada[2]

[1] Universidad Tecnológica del Centro de Veracruz. Av. Universidad No. 350 Carretera Federal Cuitláhuac - La Tinaja, Dos Caminos, Cuitláhuac, Ver., México.
[2] INFOTEC: Centro de Investigación e Innovación en Tecnologías de la Información y Comunicación. Circuito Tecnopolo Sur 112, C.P. 20313, Aguascalientes, Ags., México.
[3] CONACyT Consejo Nacional de Ciencia y Tecnología, Dirección de Cátedras, Insurgentes Sur 1582, Crédito Constructor, 03940, Ciudad de México, México.

gabriel.navarrete@utcv.edu.mx, yolanda.baca@infotec.mx
daniel.villanueva@infotec.mx,hugo.estrada@infotec.mx

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Abstract. Nowadays, the role of robotics in patients' rehabilitation it is an area of interest for science and technological development. Besides, the motor rehabilitation has had great success in subjects with disability problems which require an intensive and specific therapeutic approach for each task through robots. Budgetary constraints limit to hand-to-hand therapy approach, so machines can offer a solution to further promote patient recovery and to better understand the rehabilitation process. This article presents a ROBMMOR: an experimental robotic manipulator of knee rehabilitation. The robot is capable of performing passive exercises in patients with motor movement problems in the knee. The robot's system helps the patient in the process in a personalized way through the positions of speed and strength required. Finally, *ROBMMOR* obtains data and generates an evaluation of the progress of the patient's rehabilitation that helps the therapist for future analysis.

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Introducción

At present, rehabilitation in society has caused a great impact and technological development that has covered practically all areas of the human being. Successful motor rehabilitation in patients with accidents and traumatic injuries requires an intensive and specific therapeutic approach for each task. Smart machines can offer a solution to promote motor recovery and obtain a better understanding in rehabilitation [1]. This new field of automated or robot-assisted motor rehabilitation has emerged since the 1990s[2]. Also, robotics has had an important acceptance and successful results around robot-assisted rehabilitation. Therefore, it allows generating new alternatives for the different forms of therapies that currently exist and, as a consequence, increases the effectiveness of the exercise and diminishes the work of the expert in the domain.[3]. According to the International Classification of Functioning, Disability and Health, people with disabilities "are those who have one or more physical, mental, intellectual or sensory deficiencies and who, when interacting with different environments of the social environment, can prevent their full and effective participation in equal conditions to others" [4]. Also, according to the WHO (World Health Organization), in 1969 rehabilitation is defined as: "part of the medical care in charge of developing the functional and psychological capabilities of the individual and activate their compensation mechanisms, in order to allow them to carry an autonomous and dynamic existence" [5]. Therefore, rehabilitation seeks that the person affected or with a disability, through therapies, gradually restore their abilities, trying to reach a normal state, or at least to a state where the individual can be having autonomy, that is, to be able to fend for himself. Some of the main problems in human disabilities are caused in legs and arms causing immobility. For example, muscles weakened by old age, accidents and also neuronal problems. In order to recover the mobility of the body, the muscles have to be strengthened, through specialized exercises, for which the patient must undergo therapies carried out by expert physiotherapists who supervise and exercise the muscles of handicapped people in a manual way and, through repetitive and routine movements of damaged limbs [6]. This paper presents an experimental **ROB**otic **M**anipulator **MO**tor **R**ehabilitation of knee (*ROBMMOR*). An experimental robot capable of performing passive exercises in patients with motor problem in the knee, its system helps in the rehabilitation process. Therefore, it replaces the work and physical effort of the therapist, in addition accelerates the rehabilitation process in a personalized way through the positions of speed and strength necessary for each patient. Finally, ROBMMOR obtains data and generates an evaluation of the progress of the patient's rehabilitation that helps the expert therapist for future analysis.

State of the Art

Systems motor rehabilitation

Within the development of specialized robots for motor rehabilitation, specifically knee , there are important advances, as well as devices that are currently on the market as an attractive option for patients with disabilities [7]. For example, the case of the Optiflex 3, a unit of passive motor rehabilitation for the knee, which implements a progressive range of knee flexion, has a remote control, as well as a system that allows adjusting to the anthropometry of each patient [8]. Also, the commercial passive knee rehabilitation device is the Artromot k3, within its exclusive programming features include: heating mode settings, dual speed adjustment, patient operating time, total device operating time, features of load reversal, pause, extension and bending, making it a versatile device [9]. Within the motor rehabilitation there are several methods that physiotherapists carry out for the restoration of patients [10], within these methods we find the rehabilitation through the passive movement of the damaged limbs, which consists of repetitive movements of the joints and rehabilitation by means of active movements, where the patient performs certain exercises by himself [11].

An Spatial Augmented Reality Rehab System for Post-Stroke Hand Rehabilitation

This work presents a Spatial Augmented Reality system for rehabilitation of hand and arm movement. The table-top home-based system tracks a subject's hand and creates a virtual audio-visual interface for performing rehabilitation-related tasks that involve wrist, elbow and shoulder movements. It measures range, speed and smoothness of movements locally, and is capable to send real time photos and data to the clinic for further assessment. By developing an AR rehab system, the coordination system of user's real world is unified with the virtual world. Thus, the patients feel that the assistive virtual objects that are displayed to help them carry out their exercises, are present and belongs to real world rather to be apart in a separate screen. Also, a vision-based system was developed to locate and track the hand of the subject using color marker and motion information. The system is capable to quantify the motion captured by camera using computing vision methods. Augmented Reality technology has the potential to impact on traditional rehabilitation techniques and it could generalize to real life settings to a greater extent than other computer-based approaches [12].

Towards Engaging Upper Extremity Motor Dysfunction Assessment Using Augmented Reality Games

This work presents an exploration of the potential of Augmented Reality (AR) using free hand and body tracking to develop engaging games for a uniform, cost-effective and objective evaluation of upper extremity motor dysfunction in different patient groups. Based on the insights from a study with 20 patients (10 Parkinson's disease patients and 10 stroke patients) who performed hand/arm movement tasks in AR, a set of different augmented reality games for upper extremity motor dysfunction assessment were created. In the set of games, virtual hand visual feedback was provided to help patients interact with the virtual content. Also, visual cues were provided as 3D lines between the center of the view of the HMD (head-mounted device) and the virtual object of interest when this was located outside the view of the HMD. Depending on the hand chosen to solve the AR tasks, the whole virtual scene is mirrored. The goal of the games is to provide an objective and quantitative measurement of human motor function in a controlled and engaging environment that offers the possibility to perform a variety of movements [13].

AR-REHAB: An Augmented Reality Framework for Poststroke-Patient Rehabilitation

This work proposes a framework based on Augmented Reality (AR) technologies that can increase a stroke patient's involvement in the rehabilitation process. The approach takes advantage of virtual-reality technologies and provides natural-force interaction with the daily environment by adopting a tangible-object concept. In the framework, the patient manipulates during the treatment session a tangible object that is tracked to measure her/his performance without the direct supervision of an occupational therapist. The core architecture of the framework and its subsystems that provide more convenience to patients and therapists, were introduced. Also, two exercises are presented: a shelf exercise and a cup exercise, as examples and perform preliminary usability study. In addition, some assessment measurements such as task-completion time, compactness of task, and speed of hand movement by capturing the patients' hand movements with the tangible object were introduced. Motivating virtual objects are overlaid on top of the real scene so patients are efficiently encouraged to repeat boring and tedious rehabilitation procedures in a more pleasant way. The preliminary usability study has shown that these two key advantages are fulfilled quite well in the implemented framework [14].

Robot-Assisted Upper-Limb Rehabilitation Platform

This work presents a robotic platform for upper-limb rehabilitation robotics. It integrates devices for human multisensorial feedback for engaging and immersive therapies. Its modular software design and architecture allows the implementation of advanced control algorithms for effective and customized rehabilitations. A flexible communication infrastructure allows straightforward devices integration and system expandability. The platform is mainly composed by a robot arm, an open PC based controller, various devices to allow human-robot interaction at different levels, and a safety system which guarantee the reliability of the whole system. In the last section conclusions and future developments are drawn. In addition, the platform incorporates a stereo-vision system with a twofold purpose: completely track upper-limb and trunk movements for clinical and control feedbacks; track robot movements for safety feedback (refer to the next section). A graphic user interface has been implemented to properly control and monitor the robotic platform functionalities. It has been designed taking into account physiotherapist ergonomics using a touch-screen device [15].

Challenges and Opportunities in Exoskeleton-based Rehabilitation

Robotic systems are increasingly used in rehabilitation to provide high intensity training for patients with motor impairment. The results of controlled trials involving human subjects confirm the effectiveness of robot enhanced methods and prove them to be marginally superior over standard manual therapy in some cases. Although very promising, this line of research is still in its infancy and further studies are required to fully understand the potential benefits of using robotic devices such as exoskeletons. Exoskeletons have been widely studied due to their capability in providing more control over paretic limb as well as the complexities involved in their design and control. This work briefly discusses the main challenges in development of rehabilitation exoskeletons and elaborates more on how some of these issues are addressed in the design of CLEVERarm, a recently developed upper limb rehabilitation exoskeleton. The mechanical design of the exoskeleton is centered on reducing the weight and bulkiness of the whole structure. Robots could allow patients to start therapy in the very early stages of recovery, without having to deal with the hassles of frequent and long visits to clinics. In the comfort of their own homes, people could get specific training at the appropriate level of intensity [16].

ROBMMOR Methodology

This section describes the methodology used for the construction of the prototype. In **Fig. 1**, the *ROBMMOR* methodology is shown, which allows the design and construction of the robot. The methodology is based on recurrent engineering. On the one hand, it involves mechanical engineering for the design and construction of the robotic base. On the other hand, it involves the electronic engineer for the design and construction of the control and power plates. Finally, computer engineering for the development of the graphic interface and system programming.

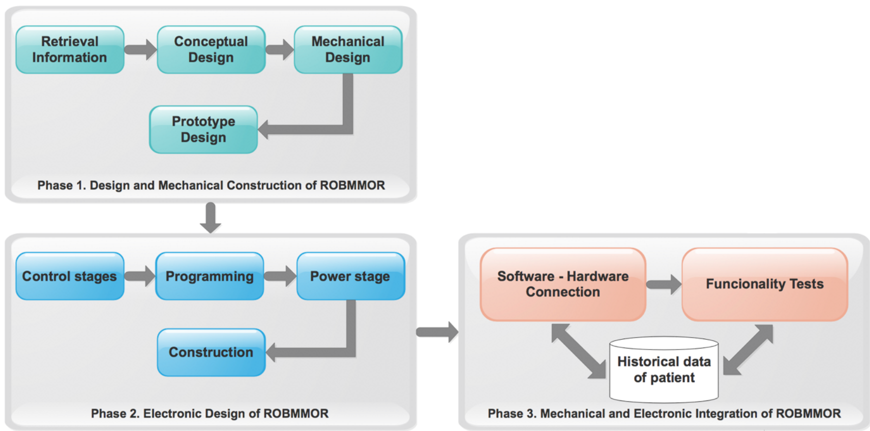


Fig. 1. ROBMMOR Methodology

Phase 1: Design and Mechanical Construction

In this phase, the development of the mechanical design that includes the recommendations of the specialist on the exercises and positions of the body that allow to move the knee is shown. Therefore, a solution is generated through the development of *ROBMMOR* for the exercise and rehabilitation of the patient. Once the information is obtained, freehand sketches are made and with industrial drawing techniques to determine the mechanical structure, obtained the base, the computer design is made through the SolidWorks software, which allows to computationally design a mechanical sketch of the Robotic platform.

Phase 2: Electronic Design

In this phase, we start to work with the electronic part, which consists in determining the actuators that will integrate the robot, considering the necessary torques and the angular movements for the knee flexion. Also, the control system and the electronic power stage are designed. Through a learning tool on the design and simulation of circuits, the designs of the plates are generated for later, in order to carry out the construction and tests of their operation. In addition, in this stage the programming algorithms for the microcontroller and the communication with the interface implemented in a computer are determined.

Phase 3: Electronic Design

In this phase the different developments of phase 1 and phase 2 are integrated. On the one hand, the mechanical, electronic design, actuators and sensors are integrated in the mechanical platform. On the other hand, the integration of the microcontroller, the control cards and the electronic power cards, is performed. Likewise, communication with the computer is developed through an interface that allows the analysis of the data. Finally, the construction of the prototype for its experimentation is carried out.

Design of the platform ROBMMOR for motor rehabilitation

3.1 Anthropometric study

To carry out the conceptual and mechanical design of *ROBMMOR,* determining factors were considered, on which the correct functioning of the system depends. The system works for different ages, consequently, the dimensions of the lower limb vary according to each factor. Therefore, it is necessary to make a study based on scientific research that serves to know the anthropometric measures on three cases of study, adults, seniors and children of the Mexican population. The measurements define the variations in the physical dimensions in which an individual belongs. **Fig. 2**, shows the anthropometric measurements of the human body.

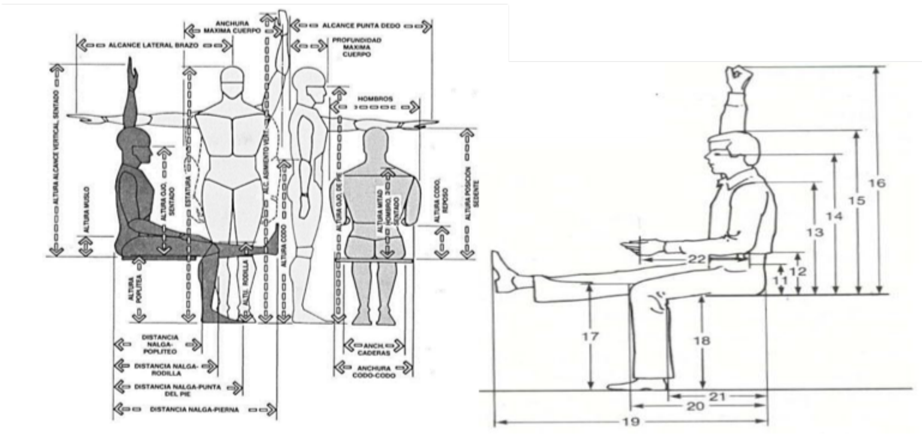


Fig. 2. Anthropometric measurements of the body.

In the case of the study on adults, the data were taken from the references of the anthropometric measurements of the body, specifically measure 12, whose study consisted of an evaluation of 210 workers whose average age was 40 years.

- Height of the floor at the knee (Measurement reference 7) - 51.84 cm.
- Height of the floor to the back of the knee (Measurement reference 18) - 43.41 cm.
- Length of the back of the knee to the back of the chair (Measurement reference 21) - 49.83 cm.
- Knee length at the back of the chair (Measurement reference 22) - 60.60 cm.

For the case study of the elderly according to measurement reference 13, for a population with an average age of 66.9 for men and 67.3 years for women, with a sample of 508 individuals, the results are the following:

- Men's knee height: 52.04 cm.
- Women’s knee height: 47.94 cm.

In the case of children's anthropometric study, the data were taken from the measurement reference 14 for an average age of 10 years:

- Floor height at the knee - 39 cm.
- Knee length at the back of the chair - 48.3 cm.

3.2 Analysis of the strength of the knee joint

The strength of the knee joint used to determine the necessary torque needed to move a person's knee and, in this way, determine the power and type of physical motor to be used within the system. According to the study carried out in measurement reference 15 of **Fig. 2**, which consisted in determining the strength of the knee joint in both flexion and extension, A 40 people sample was selected, which was composed by 20 men and 20 women, with the help of a Biodex 3 dynamometer team, which will help determine the angles and average strength. The selected people with an average age of 30.7 years, average height equal to 1.74 m in men and 1.57 in women, and with an average weight of 81.7 kg in the case of men and women. 57 kg in the women's [17]. Table 1, 2, 3 and 4, show the results of the case study.

Table 1. Torque of the flexion of a man's leg

Leg	Degrees	Average torque in flexion
Right	60°	107.806 Nm
	90°	98.456 Nm
	120°	98.722 Nm
Left	60°	101.622 Nm
	90°	96.706 Nm
	120°	89.350 Nm

Table 2. Payment Management Torque of the spread of a man's leg

Leg	Degrees	Average torque in extension
Right	60°	189.156 Nm
	90°	182.861 Nm
	120°	153.694 Nm
Left	60°	181.911 Nm
	90°	164.694 Nm
	120°	152.622 Nm

Table 3. Flexion torque of a woman's leg

Leg	Degrees	Average torque in flexion
Right	60°	56.040 Nm
	90°	50.360 Nm
	120°	49.180 Nm
Left	60°	54.920 Nm
	90°	48.615 Nm
	120°	46.940 Nm

Table 4. Torque of the extension of a woman's leg.

Leg	Degrees	Average torque in extension
Right	60°	107.020 Nm
	90°	89.580 Nm
	120°	83.705 Nm
Left	60°	102.860 Nm
	90°	89.335 Nm
	120°	81.620 Nm

The data show that the highest value is the extension force of a man's right leg, the magnitude is 189.156 Nm of torque. Therefore, the motor must provide a greater force to consider, not only the weight of the knee, but also the support that raises the leg. Also, it is necessary to consider that in the passive movement the knee must be moved even though the patient puts some resistance. However, care must be taken in order to avoid damaging the patient's joint.

3.3 Physical design of the robot

The most appropriate way to perform knee rehabilitation exercises is with the patient sitting, So that, we decided build the mechatronic system based on the design of a chair or exercise bench, since this device is comfortable; once the bank was physically developed a sketch of the mechatronic system was designed. In **Fig. 3**, the different stages of design are shown, from the idea to using freehand drawings of a bank of exercises, considering that the patient needs to be comfortable, and to have a support to be able to sit, until the computer design which allows to obtain simulations of the movements of the mechanisms involved. Finally, the *ROBMMOR* prototype is shown.

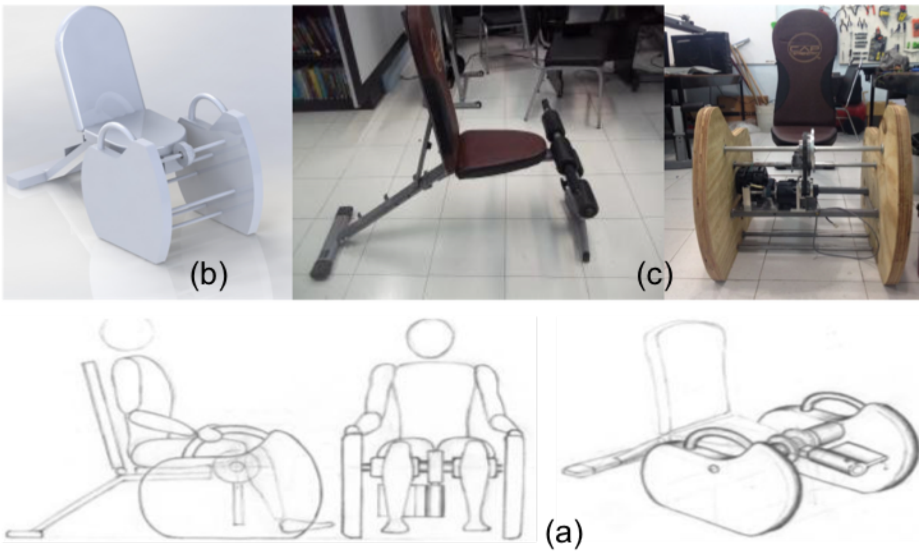


Fig. 3. Stages of design (a) Design on freehand drawings, (b) Computer design (c) ROBMMOR prototype.

3.4 Robot control design

This section describes the development of the *ROBMMOR* system for knee rehabilitation. The electronic design is responsible for driving the motor, controlling the speed and controlling the force applied by the device to the patient's leg. In addition, the electronic design can control over the position to determine the degree of flexion and extension. Finally, the strength that each patient applies through a communication between the computer and the prototype is recorded. In the speed control of the prototype, a converter cycle was designed and implemented to control the engine speed. Therefore, it allows to control the speed with which the device flexes the knee of the patient through the electric motor who provides the necessary power to do perfom it. The motor to be controlled is single-phase induction with capacitor start, its nominal current is 1.5 A, its supply voltage is 120 V at 60 Hz with a nominal speed is 1750 rpm and a power of 1/20 HP. This engine within the system is coupled to a gearbox with which its speed is reduced and its torque is increased, the reduction ratio is 200: 1. Also, an incremental quadrature encoder is used for position control, the encoder has two main channels called A and B and a third channel that helps find the initial position called Index and, this encoder inside the prototype is installed in the speed reducer shaft. (see **Fig. 3**).

In **Fig. 4**, the block diagram of the electronic control system of *ROBMMOR* is shown. The diagram starts from a CA (Alternating Current) and, it goes to a rectification stage controlled by SCRs (Silisium Controlled Rectifiers). The obtained signal is filtered and taken to an inverter circuit designed with Mosfets. Then, the inverter that is controlled by the microcontroller using the sinusoidal PWM technique, generates an output signal with variation in frequency, this signal goes directly to the motor, which has a speed reducer and an incremental encoder installed, the signal of the sensor is sent to the microcontroller, the setPoint of the system is sent by the user interface to the microcontroller which finally sends the signals.

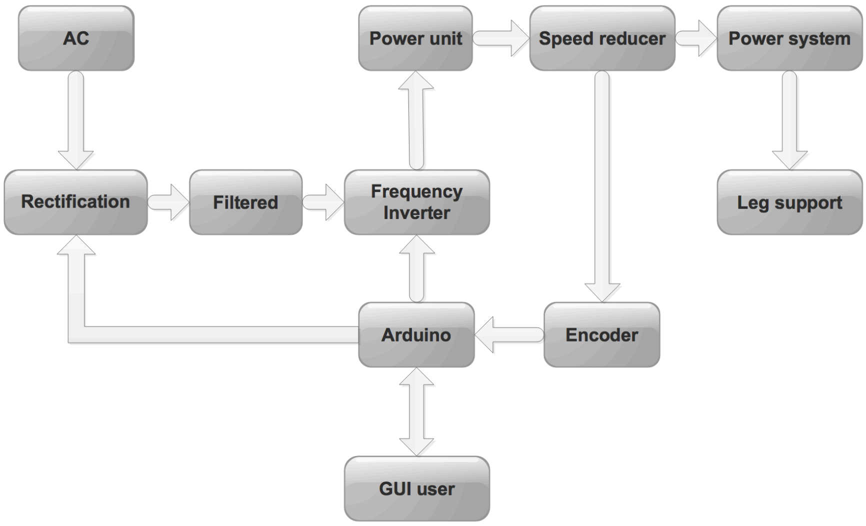


Fig. 4. Block diagram of electronic system.

In the case of the robotic system to be able to control the speed of the single-phase induction motor, the current of the AC supply must first be converted to CD, the DC potential level must be regulated, and then converted from CD to AC, but the AC frequency must be modulated, which results in a CA to AC cycloconverter. Which provides to the output a regulated potential and a modulated work frequency.

Discussion and evaluation

Modulation with sinusoidal PWM technique

Modulation with sinusoidal technique consists of emulating the behavior of a sine wave through the control of pulse width in time intervals. The technique uses a signal of nine pulses per quarter of cycle, each pulse must increase in duration until it reaches the quarter of a cycle where, the next quarter of a cycle, the pulses decrease. To apply this signal to the inverse of full bridge it is necessary to generate two signals but with a phase shift. **Fig. 5**, shows the modulation of *ROBMMOR* with the sinusoidal technique through a microcontroller and the simulation of its outputs.

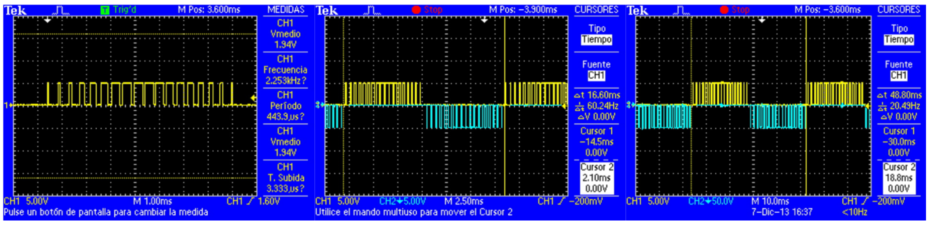


Fig. 5. Waveform of the two sinusoidal PWM signals of the microcontroller.

4.2. Graphic interface

For the design of the graphical interface there is a database for the end user. At the base, data is stored, such as the name, the description of the motor problem presented by the patient. resents, the therapist's observations according to the progress shown in the rehabilitation, among others. The data is accessed through the file with the patient's name. The interface shows the control parameters for the routine, the duration time of the routine, the speed, the degrees of flexion and extension. Finally, the stop and start control and the start control of the routine (see **Fig. 6**).

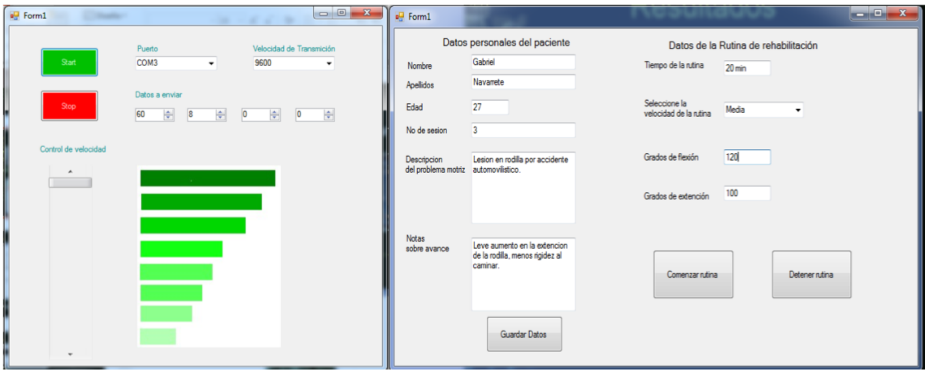
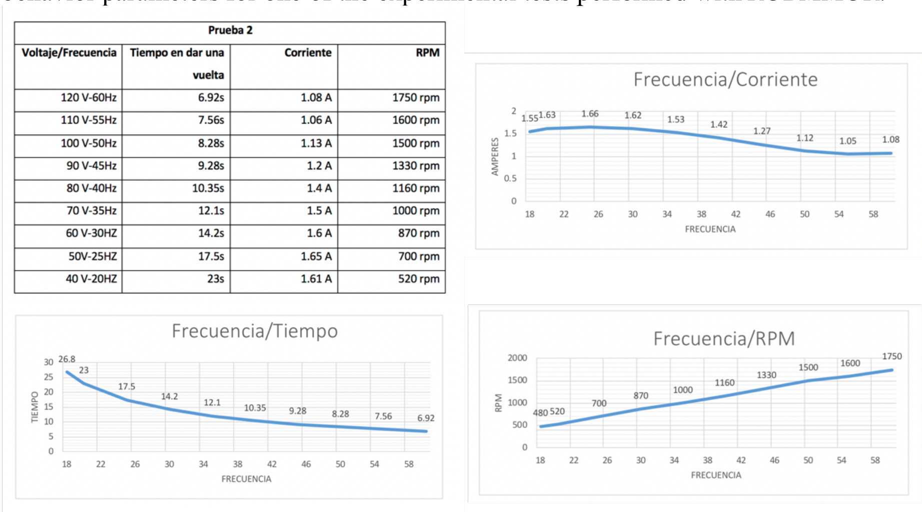


Fig. 6. Graphic interface ROBMMOR

According to the calculations obtained through the anthropometric analysis, the correct functioning of *ROBMMOR* is ensured. Therefore, a torque capable of lifting a 10 kg leg is obtained. By graphs obtained from the behavior of the current and voltage, and by means of position and speed control, the pertinent routines can be programmed for therapy. In addition, varying the frequency and power supply of the motor, it can be determined if the robot can lift the desired weight. **Fig.** *7*, shows the graphs and the behavior parameters for one of the experimental tests performed with *ROBMMOR.*



Prueba 2			
Voltaje/Frecuencia	Tiempo en dar una vuelta	Corriente	RPM
120 V-60Hz	6.92s	1.08 A	1750 rpm
110 V-55Hz	7.56s	1.06 A	1600 rpm
100 V-50Hz	8.28s	1.13 A	1500 rpm
90 V-45Hz	9.28s	1.2 A	1330 rpm
80 V-40Hz	10.35s	1.4 A	1160 rpm
70 V-35Hz	12.1s	1.5 A	1000 rpm
60 V-30HZ	14.2s	1.6 A	870 rpm
50V-25HZ	17.5s	1.65 A	700 rpm
40 V-20HZ	23s	1.61 A	520 rpm

Fig. 7. Experimental test of frequencies with ROBMMOR.

The sequences and control strategies for the execution of *ROBMMOR* are programmed from the graphic interface. Through the interface, the patient's history and the data of each routine, can be stored. The data stored provides a personalized record of the progress of the exercises carried out. Subsequently, the records can be used to analyze the results and monitor the patient's rehabilitation progress, and also, it can generate an alternative for the expert. Also, *ROBMMOR* ensures that the torque is enough to lift a human leg, the experimentation was done with different weights of 8kg., 9kg., 10kg. and a maximum 12kg. to check the *ROBMMOR* positions.

5. Conclusions and Future Works

By means of the design and construction of *ROBMMOR* it is possible to verify that the electronics, robotics, computer science and the techniques for the development involved in the robot, allow the experimental manipulation in the technological development for the motor rehabilitation of the knee. There is an area of opportunity that can be addressed with the present development, or the case of people who are disabled by a motor problem or a disease that damages some of their body members. Likewise, the technological development of *ROBMMOR* benefits people with a motor disability. The robot is a complementary tool for therapists in the treatment and diagnosis of patients. Besides rehabilitation centers are benefited with this type of technological advances as part of a possible clinical application for users. On the one hand, by providing a robot that allows them to save physical effort and work time. On the other hand, to provide better control in motor rehabilitation therapies of the knee.

The data stored provides a personalized record of the progress of the exercises carried out. Subsequently, the records can be used to analyze the results and monitor the patient's rehabilitation progress, and also, it can generate an alternative for the expert. The evaluation of the design shows that the manipulator robot has enough strength to be able to lift a human leg and sufficient speed and position accuracy to guarantee the correct execution of the exercises.

Passive rehabilitation by the patient is accomplished by having an exact control over the position of the flexion-extension of the leg. Therefore, *ROBMMOR* can bring an adequate rehabilitation therapy according to the needs of patients with knee problems. Furthermore, it allows to have a more orderly control of the process of improvement of movements. The programming used in *ROBMMOR* allows to obtain a scope for the successful improvement in the routines programmed in the rehabilitations. As future work, it is intended to implement an active rehabilitation in studies with patients, to enhance *ROBMMOR* with a virtual reality system and a security system for the physical integrity of people who use the prototype

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