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Mechatronic System for Knee-Ankle Rehabilitation

Sistema Mecatrónico para Rehabilitación de Rodilla-Tobillo

ESPINOSA-VAZQUEZ, Rogelio†, VAZQUEZ-MARTINEZ, Mariana, CHARRE-IBARRA, Saida*, and GUDIÑO-LAU, Jorge

Universidad de Colima, Facultad de Ingeniería Electromecánica, Carretera Manzanillo-Barra de Navidad Km. 20.5, El Naranjo, 28860, Manzanillo, Colima, México

ID 1st Author: *Rogelio, Espinosa-Vázquez* / **ORC ID**: 0000-0002-6105-9642

ID 1st Co-author: *Mariana, Vázquez-Martínez* / **ORC ID**: 0000-0002-6489-5398

ID 2nd Co-author: *Saida, Charre-Ibarra* / **ORC ID**: 0000-0002-3823-5388, **Researcher ID Thomson**: Q-6851-2018, **arXiv Author ID**: saidacharre

ID 3rd Co-author: *Jorge, Gudiño-Lau* / **ORC ID**: 0000-0002-0585-908X, **Researcher ID Thomson**: Q-6844-2018, **arXiv Author ID**: jorgeglau

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Abstract

This paper describes the design and construction of a mechatronic system that aims to support physical therapies for the rehabilitation of the knee and ankle, assisting the patient in flexion and extension movements. The system consists of a mechanism that can be adapted to the patient, a data acquisition stage consisting of an Arduino and a virtual interface programmed in LabVIEW. The above in order to achieve a continuous passive movement device that reduces stiffness and pain in the joints, generating a gradual and slow movement determined by the physiotherapist.

Rehabilitation, Ankle, Knee, Mechatronics, Assive exercise

Resumen

En el presente trabajo se describe el diseño y construcción de un sistema mecatrónico que tiene la finalidad de apoyar en terapias físicas para la rehabilitación de la rodilla y el tobillo, asistiendo al paciente en movimientos de flexión y extensión. El sistema está compuesto por un mecanismo que se puede adaptar al paciente, una etapa de adquisición de datos conformada por un Arduino y una interfaz virtual programada en LabVIEW. Lo anterior con el propósito de lograr un dispositivo de movimiento pasivo continuo que reduzca la rigidez y dolor en las articulaciones, generando un movimiento gradual y lento determinado por el fisioterapeuta.

Rehabilitación, Tobillo, Rodilla, Mecatrónica, Ejercicio pasivo

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* Correspondence to Author (e-mail: scharre@ucol.mxc)
† Researcher contributing first author

1. Introduction

The knee joint is one of the most complex joints in the body, made up of ligaments, which are responsible for regulating joint kinetics and inform the periarticular musculature, influencing the position of the articular surfaces, the direction and magnitude of the forces, with the knee being one of the most affected musculoskeletal injuries, and within it, in 9% of cases ligament injuries occur, the most common being anterior cruciate ligament (ACL) rupture. This injury is highly prevalent in the general population, especially in sports activities such as running, contact sports and especially in football, where this injury has a higher incidence due to turns and changes of direction. A large percentage of these injuries require surgical treatment.

The rehabilitation process includes a pre-surgical stage and a post-surgical stage. It is in the post-surgical stage that action is taken to increase the mobility and articular arc, tone and muscle power of the muscles involved in knee movements, especially the quadriceps femoris, the common extensor par excellence, which is of paramount importance in maintaining knee stability, so that the knee rehabilitation device is able to perform repetitive extension and flexion movements, which is necessary for rehabilitation.

The human body, despite being a very strong and resistant structure, can suffer some alterations. Between each of the activities that are performed every day, our body wears out causing some injuries. Knee injuries are common, especially when playing sports. The most common are those that occur in the soft tissues (ligaments and tendons). However, it is also possible for the bones to be damaged.

Knee injuries in young patients (between 20-30 years of age) are usually associated with sporting activities. However, injuries from falls and road accidents are also part of the statistics (Peña, 2019).

On the other hand, the ankle is a complex, weight-bearing joint that is exposed to high rotational stresses, which can lead to injury. Approximately 10% of fractures that are diagnosed are ankle fractures (with an upward trend), this high incidence makes it a very relevant entity nowadays (Porras et al., 2022).

The control, monitoring and communication of automated systems bring with them a series of technologies in constant development that aim to facilitate processes. In the health area, in traumatology to be precise, usually the rehabilitation process of patients is directly assisted by the physiotherapist and the rehabilitation results or improvements of the patient are merely empirical results.

With the purpose of assisting in the procedures carried out in the rehabilitation of patients, a mechatronic system capable of making the continuous passive movements required for rehabilitation is developed.

2. Rehabilitation

Rehabilitation is the care that a patient receives to recover, maintain or improve the abilities needed for daily life. These abilities can be physical, mental and/or cognitive (thinking and learning) (Metlineplus, 2019).

These abilities may be lost or impaired by illness or injury, or as a side effect of medical treatment. Rehabilitation can and does aim to improve their daily life and functioning. It is intended for people who have lost normal ability to function, often as a result of injury, stroke, infection, tumour, surgery or progressive disease (such as arthritis) (Portugal & Grossman, 2021b).

Types of rehabilitation

Orthopaedic rehabilitation: Orthopaedic rehabilitation is the medical discipline that assesses, diagnoses and treats physical pathologies ranging from muscle strain to fractures or severe injuries, and even congenital conditions such as flat feet (TherapyCord).

Neurological rehabilitation: Neurological rehabilitation is intended to help people with diseases, injuries or disorders of the nervous system.

According to Anne Fetterman (2021), some of the conditions that neurological rehabilitation can help improve are:

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– Vascular disorders, such as stroke, bleeding in the brain or transient ischaemic attacks (TIAs).

– Infections, such as meningitis, encephalitis, polio and brain abscesses.

– Trauma, such as brain and spinal cord injuries.

– Structural or neuromuscular disorders, such as facial paralysis, cervical osteoarthritis, brain or spinal cord tumours, myasthenia gravis, etc.

– Functional disorders, such as headaches, seizures, dizziness and neuralgia.

– Degenerative disorders, such as Parkinson's disease, multiple sclerosis, amyotrophic lateral sclerosis (ALS), Alzheimer's disease and Huntington's chorea.

Geriatric rehabilitation:

Geriatric rehabilitation is the set of social activities aimed at seeking the best incorporation of the elderly into micro, and macro society. It is a daily effort integrated by a multidisciplinary team to return them to a better functional and socio-environmental state that helps them to maintain or maximise function when full recovery is not possible (Rodríguez, 2009).

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In general, the goal of rehabilitation is to help the patient regain their abilities or independence; while the specific goal will depend on the situation in which each patient finds themselves; this will depend on the cause of the problem, whether the cause is ongoing or temporary, what abilities were lost and how severe the problem has been. Similarly, the type of rehabilitation to be carried out will depend on what is to be achieved. There are three types of mobility-enhancing exercises:

Active exercise

This type of exercise is suitable for those who can maintain muscle or joint activity without assistance. They must move their limbs on their own.

Assisted active exercise

This type of exercise is suitable for people who can move their muscles or joints but cannot do so without pain. They move their limbs on their own, but the therapist helps them to do so, either manually or with the help of bands, belts or other suitable equipment.

Passive exercise

This type of exercise is suitable for those who cannot actively participate in the procedure. No effort is required of them. The therapist moves their limbs to avoid contractures (the permanent stiffening of muscles as a result of lack of movement), among other objectives (Portugal & Grossman, 2021a).

3. The knee

The knee is a joint that is located in the middle of the lower limbs and has the function of supporting the weight and giving mobility when walking, running, jumping or any movement that is done with the legs; because of this, it is important that the knee is kept mobile and stable, since there are many structures that are found in it that are responsible for giving movement to the legs and stability to it, such as muscles, ligaments, menisci, tendons and other structures, as can be seen in Figure 1, the knee joint is formed by three bones: the thigh bone (femur), the leg bone (tibia) and the patella (Alameda, 2021).

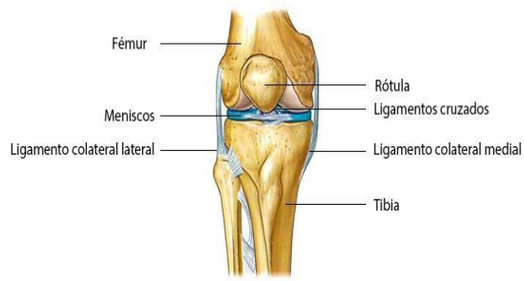

Figure 1 Knee anatomy
Source: Alameda, 2021

The knee is a sensitive joint that is very often damaged. There are several reasons for this, but the most common are progressive degeneration due to age, excessive overweight overloading the body at this vital point of the limb, and of course, other bone diseases.

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The three most common knee injuries are:

Torn ligaments

Ligaments are elastic bands of tissue that connect bones together and provide stability and strength to the joint. They connect the femur (thigh bone) to the tibia (shin bone). The four main ligaments in the knee are:

- Anterior cruciate ligament (ACL). The ligament, located in the centre of the knee, that controls rotation and forward movement of the tibia (shin bone).
- Posterior cruciate ligament (PCL). The ligament, located at the back of the knee, that controls backward movement of the tibia (shinbone).
- Medial collateral ligament (MCL). The ligament that gives stability to the inner knee.
- lateral collateral ligament (LCL). The ligament that gives stability to the outer knee.

Meniscal injury

Each knee has two C-shaped pieces of cartilage that act as a cushion between the shin bone and the thigh bone. A torn meniscus causes pain, swelling and stiffness. You may also feel a blockage in the movement of the knee and have trouble extending it fully (Litin, n.d. b).

Patellar tendon injury

The patellar tendon is part of the knee extensor apparatus, connects the patella to the tibia and represents the continuation of the quadriceps below the patella and is essential for the extension of the knee joint (Arnal, n.d. a).

Primarily the knee has only one degree of freedom of movement, i.e. flexion and extension. This movement allows the knee to regulate the distance of separation of the body from the ground, this is achieved by moving the end of the leg closer or further away from the root of the leg, i.e. by moving the buttock closer or further away. In addition to this main sense of freedom, the knee has an ancillary degree of freedom, which occurs only in flexion. This movement is one of rotation about the longitudinal axis of the leg.

The knee joint performs two functions that can be contradictory:

It must possess great stability when in full extension, at which point the knee bears the weight of the body.

It must have great mobility in flexion, as it must provide the foot with good orientation during walking.

Extension movement

It is in this movement where the posterior aspect of the leg moves away from the thigh, in reality there is no absolute extension of the leg, however, if a maximum extension is reached in the reference position; on the other hand, from the maximum extension a movement can be performed passively, from 5° to 10° of extension, called hyperextension. Active extension is when the knee is in active extension, it does not usually go beyond the reference position, this depends on the position of the hip. In fact, hip extension, which occurs prior to knee extension, prepares for knee extension. Relative extension is a complementary movement for knee extension from any position. This is the normal movement of the knee during gait: it is when the swinging limb comes forward to contact the ground (Leonardo, 2008).

Flexion movement

This movement is the reverse of extension, as shown in Figure 2, where the back of the leg approaches the back of the thigh, in flexion there are movements known as absolute flexion which occurs from the reference position and relative flexion movements found in any flexion position (Leonardo, 2008).

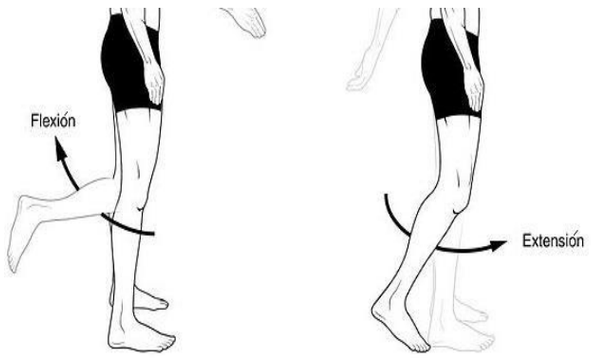

Figure 2 Knee flexion and extension
Source: Moriani, 2017

4. Ankle

The ankle is made up of the tibia, fibula (also called fibula), talus and calcaneus, Figure 3, divided into two joints, the tibio-ankle and subtalar joints, which allow dorsiflexion, plantar flexion, inversion and eversion (Zaragoza-Velasco & Fernández-Tapia, 2013).

Figure 3 Ankle bone anatomy
Source: Zeledon, s.f.

The Achilles tendon, Figure 4, is the largest tendon in the body, connecting the muscles of the back of the calf (soleus and calf) to the heel bone and is the most powerful tendon in the entire body. Although it is the thickest and strongest tendon, during jumping activities it can withstand forces of up to 7 times body weight, which repeatedly represents a high mechanical demand. Its function is to flex the foot downwards, and it is used virtually every time the foot is walked and moved. In addition to acting as an ankle motor, it acts as a force absorber every time you land from a jump, so in addition to acting during its concentric function, it is vital in preventing foot extension in its eccentric function (Arnal, n.d. b).

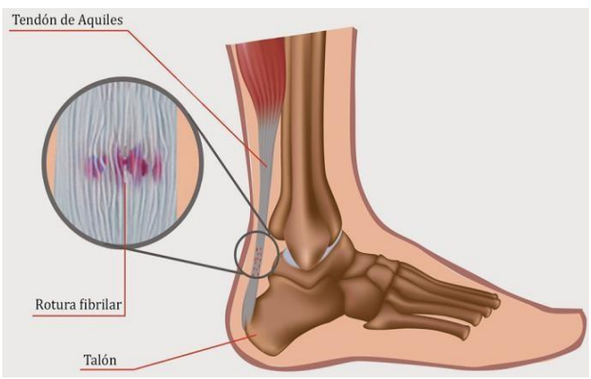

Figure 4 Achilles tendón
Source: Arnal, s.f. b.

Common injuries to the Achilles tendon include tendonitis (inflammation), tendinosis (degeneration) and rupture. This tendon can rupture due to overuse or injury, such as a direct blow to the lower leg or ankle. It is usually torn when the calf contracts while an external force stretches it. Symptoms include severe pain and a snapping sound at the time of injury, followed by swelling and inability to stand or point with the toes (Litin, 2022a).

This type of injury is most common in athletes or people in their 30s and 50s, but can affect anyone. Complete rupture is more common in men.

In the ankle, two joints stand out: the tibioperoneoastotalar joint, which is the main joint, and the lower peroneotibial joint (fisiofocus, 2014), Figure 5.

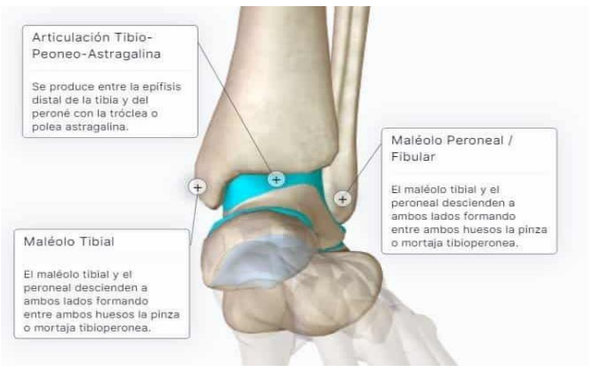

Figure 5 Ankle joints
Source: Fisiofocus, 2014

The ankle has one main movement, this takes place in the longitudinal plane and it is the movement of plantar and dorsal flexion of the foot; dorsal flexion or extension is defined as the movement that brings the dorsum of the foot closer to the anterior aspect of the tibia; while plantar flexion is the opposite movement, of greater amplitude and it produces the decompression of the joint and sliding (Litardo et al., 2021).

It is commonly accepted that there is about 10-30° of dorsiflexion and about 20-50° of plantar flexion, Figure 6.

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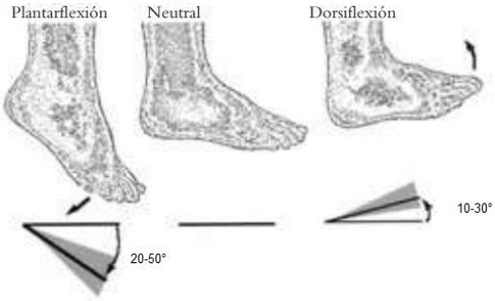

Figure 6 Main movement of the ankle
Source: Sous, 2011

5. Continuous Passive Motion Therapy

Continuous Passive Motion (CPM) therapy involves placing the affected joint in a specially designed motorised device that continuously and passively moves the joint through a set degree of ROM (joint range of motion).

A CPM, also known as a passive knee mobiliser, uses passive motion to move the joint gradually and slowly without engaging the patient's muscles. The physiotherapist will prescribe the instructions for use, including the speed of the machine, duration of use, amount of movement and speed of movement.

A continuous passive motion device maintains movement of a joint after limb-sparing surgery, as shown in Figure 7. This motion reduces stiffness and pain, so it is important to keep the joints moving after surgery so that joint movement is not limited; it is also used after surgery to help pump fluid out of the joint by reducing the accumulation of blood and fluid in and around the joints (St. Jude Children's Research Hospital, 2018).

The device can be applied as a rehabilitative device in the following cases:

– Arthroscopy and arthrotomy procedures.
– Plastic reconstruction of cruciate ligaments.
– Surgical treatment of fractures and pseudoarthrosis.
– Total knee / hip replacement.
– Ankle sprain.

Figure 7 Continuous passive motion at the knee
Source: Fainer, 2021

6. Prototype design

After previous research on continuous passive movements for rehabilitation, it was determined that the crank-crank-slide mechanism reproduces the movements required in the rehabilitation procedure, Figure 8.

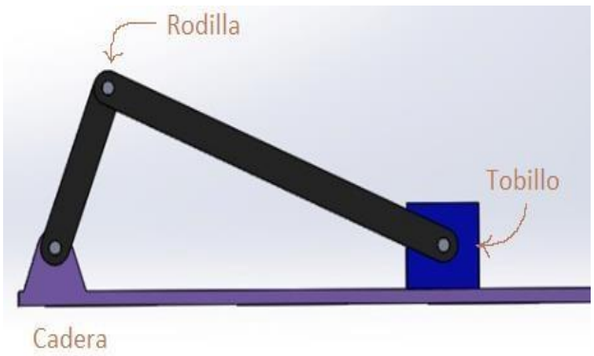

Figure 8 Crank-crank-slide mechanism
Source: Own Elaboration

Figures 9 and 10 present the design drawings of the mechanism for rehabilitation.

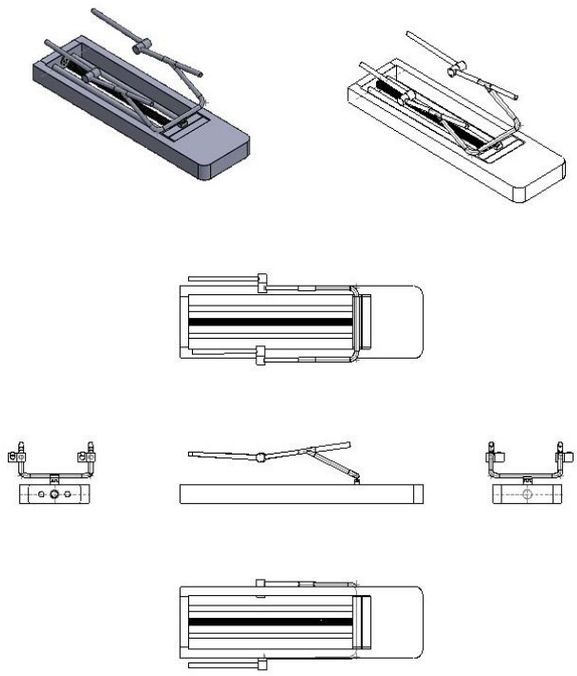

Figure 9 Crank-crank-slide mechanism
Source: Own Elaboration

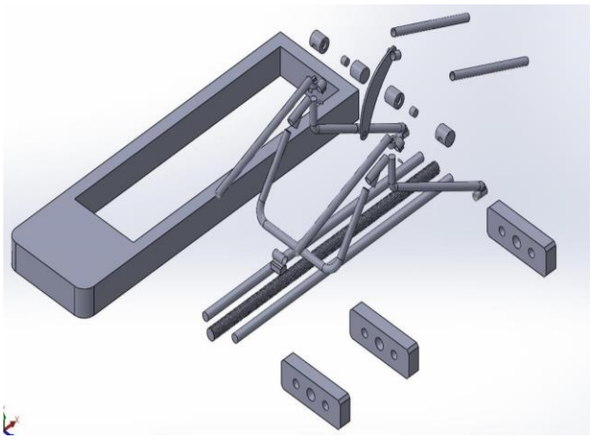

Figure 10 Design of the mechanism
Source: Own Elaboration

Figure 11 shows the mechanism of the prototype under construction.

Figure 11 Mechanism
Source: Own Elaboration

7. Mechatronic system interface

Figure 12 shows the diagram of the main components that make up the mechatronic system for rehabilitation. It can be seen that the data acquisition system that communicates the virtual interface developed in a computer with the prototype mechanism uses an Arduino microcontroller.

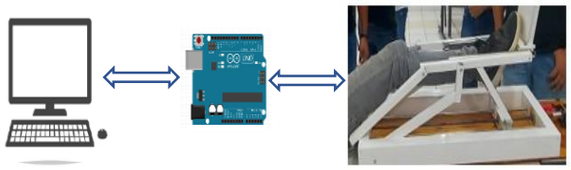

Figure 12 System diagram
Source: Own Elaboration

Figure 13 shows the block diagram corresponding to the mechatronic system designed to rehabilitate the knee and ankle.

The support user will be in charge of interacting with the control interface, in which there is a panel with virtual buttons and knobs, through which the selected data and values will be sent to the Arduino; subsequently the control signal will be sent to a stepper motor and in this way the mechanism in charge of performing the knee movements (extension and flexion) will start to work, which will be reflected in the patient in rehabilitation.

On the other hand, the servomotor, when selected in the control interface, will be in charge of carrying out the movements of the ankle (extension and dorsiflexion) which will be noticeable in the patient. The optical sensor will send data to the Arduino, which can be seen on the interface in the Calibration Panel section (green indicator), this means that the position of the knee mechanism is in the indicated position to start with the knee rehabilitation.

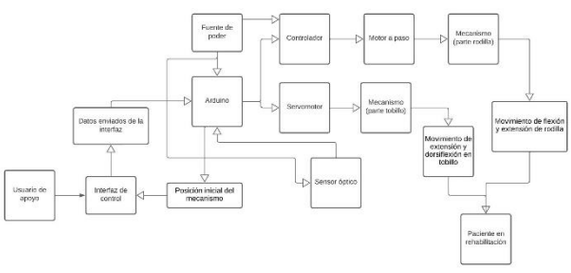

Figure 13 Block diagram
Source: Own Elaboration

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Figures 14 and 15 show the virtual interface and block diagram, programmed in LabVIEW software, for the rehabilitation task.

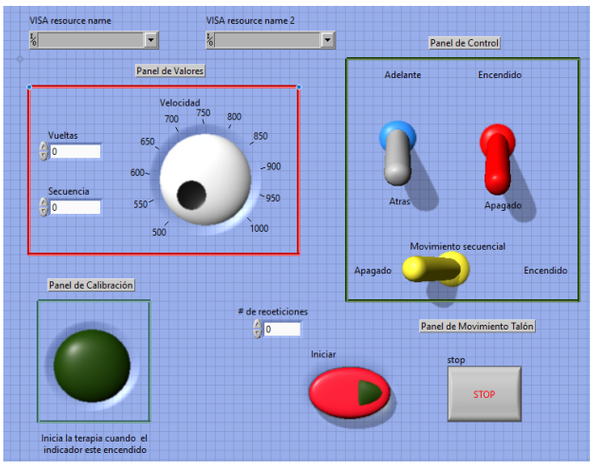

Figure 14 Virtual interface
Source: Own Elaboration

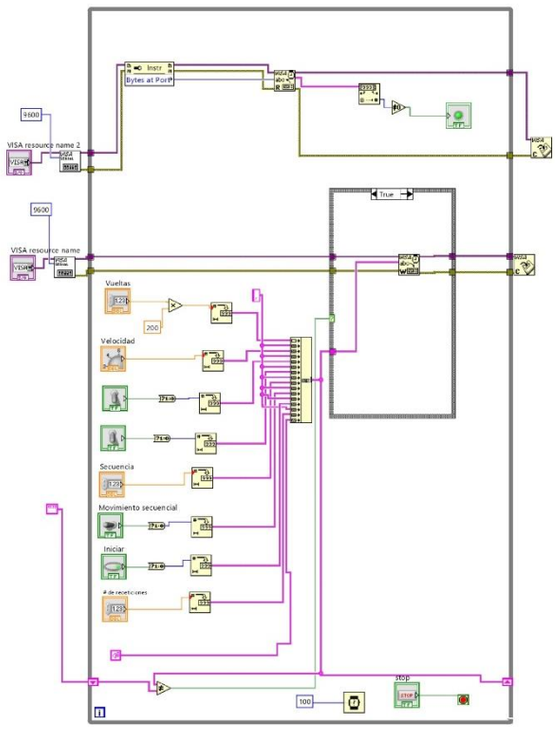

Figure 15 Programme block diagram
Source: Own Elaboration

8. Results

In Figures 16 and 17, the final result is the continuous passive motion prototype, built to support the rehabilitation procedure of the knee and ankle in patients with stiffness and pain conditions.

Figure 16 Prototype
Source: Own Elaboration

Figure 17 Prototype testing
Source: Own Elaboration

Acknowledgements

To the Faculty of Electromechanical Engineering of the University of Colima.

Conclusions

Rehabilitation is an important part of universal health coverage, it helps people to have a higher degree of independence in their daily life activities and it is estimated that the need for rehabilitation will increase in the world due to the changes and characteristics of the population.

Due to the above and the increasing application of technology for human welfare, a prototype was developed that performs functions that are present in traditional physical rehabilitation, which consists of direct manipulation by physiotherapists of patients. The mechanism allows the extension and flexion of the knee and the ankle, achieving the planned objective.

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As future work we intend to add more functions to the virtual interface, which will be determined by future testing of the prototype.

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