Telerehabilitation for People with Knee Mobility Injuries

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Abstract. Nowadays, telerehabilitation is a feasible alternative to traditional rehabilitation services. In this context, we present a bilateral tele-rehabilitation system for people with knee injuries, through the execution of remote rehabilitation routines. The rehabilitation prototype is designed in CAD/CAE software; given its complexity, the finite element method is used to detect possible failures due to the dimensioning and the safety factor. The system control scheme is based on autonomous control algorithms and bilateral teleoperation theory. At the local station, the physiotherapist generates rehabilitation routines using the Novint Falcon haptic device and a computer; the information sent to the remote station is received and the patient interacts with the prototype by executing the programmed flexion and extension movements. In addition, the physiotherapist receives visual, auditory and force feedback from the remote site for better system transparency. Finally, the experimental results show the performance of the proposed system. Usability tests are also conducted with different users in an experimental environment.

Keywords: Telerehabilitation, Mechanical Design, Autonomous Control, Haptic device.

1 Introduction

Disability is a condition that limits a human being's ability to perform everyday activities [1]. Persons with disabilities include those with physical, mental, intellectual or sensory impairments [2]. About 15% of the world's population has some type of disability [3]. It is likely that almost everyone at some point in their lives will experience some type of disability, whether temporary or permanent [3]. One of the main causes of this physical limitation are injuries [4]. In terms of lower extremity injuries, knee injuries are the most frequent [5]. This knee trauma is a risk factor for the development of knee osteoarthritis in young adults, with four to six times higher odds, compared to an uninjured knee [6].

In recent years, technological and medical advances have gone hand in hand, through the development of different lines of application with essential devices for the prevention, diagnosis and treatment of diseases; relevant in rehabilitation [7]. Globally, an estimated 2.4 billion people have a health condition, which benefits from rehabilitation [8].

Physical rehabilitation is essential to mitigate and restore a person from the adverse effects acquired from various disabilities, and to improve independence and quality of life. [9]. Science and engineering have made it possible to modify existing technologies and develop new ones to optimize rehabilitation, specifically with equipment based on virtual reality, brain-computer interface, neural systems, wearable devices, and IoT [10]. Therefore, there is support and rehabilitation equipment for most parts of the human body, such as: intelligent wheelchairs, 3D bioprinting of anatomical models of customized prostheses, motorized exoskeletons, and robotic assistive devices [11] [12]. In addition, these devices have allowed the therapist to quantitatively measure the patient's performance and progress [13].

Similarly, lower extremity rehabilitation technologies have been developed that provide an efficient outcome in post-surgical or post-injury rehabilitation, due to the advantages of accuracy and reliability they offer [14]. ese robotic devices do not replace the therapist, they must always be under the supervision of the therapist [11]; for example, Lokomat and LokoHelp, are exoskeletal robots with virtual reality for rehabilitation of neurological patients, which perform walking movements on a treadmill [14]. Another device is Riablo, which uses video with a treadmill, this orthopedic rehabilitation platform allows patients to play video games while performing the exercises prescribed by the therapist [13].

Currently, there are several proposals based on telecommunications to support and strengthen rehabilitation processes with better coverage. Therefore, telerehabilitation emerges as a support tool for specialists in the management of the registry, history of the evolution and diagnosis of patients in motor rehabilitation processes remotely [15] [16]. The purpose is to offer timely care, increasing accessibility and continuity of care for populations with disabilities, especially those in vulnerable and geographically remote situations [17] [18]. With the arrival of the COVID 19 pandemic, it became much more important and for months became the best way of rehabilitation [19] [20].

In this context, the present research work proposes a bilateral telerehabilitation system for people with knee injuries, who are in the recovery stage, focused on the flexion and extension movements of the joint. The proposed prototype must be ergonomic and functional. Therefore, the design of the structure is based on the anthropometric measurements of adults. In addition, sensors and actuators are implemented in the prototype, in order to perform telerehabilitation tasks in an autonomous and therapist-assisted way. As for teleoperation, it consists of three main stages: a) *local station*, where the therapist in charge of managing and monitoring the rehabilitation routines is located; b) *remote station*, where the patient is located with the rehabilitation prototype; y c) *communication channel*, that which allows interaction between the local station and the remote station using internet connection. Finally, the results obtained are presented, validated by means of experimental tests and a usability test to evaluate the acceptance of the developed system.

The following document consists of five sections, including the introduction. Section two describes the methodology for the development of the telerehabilitation system. Section three explains the teleoperation and stand-alone control scheme. Section four presents the results obtained from the experimentation, as well as the percentage of usability of the telerehabilitation system. Finally, section five presents the conclusions.

2 Methodology

Fig. 1 shows the implemented methodology of the telerehabilitation system for people with knee mobility injuries. The methodology is subdivided into four main stages, in which functionality, ergonomics and safety requirements that meet the needs of the therapist and patient were considered [21].

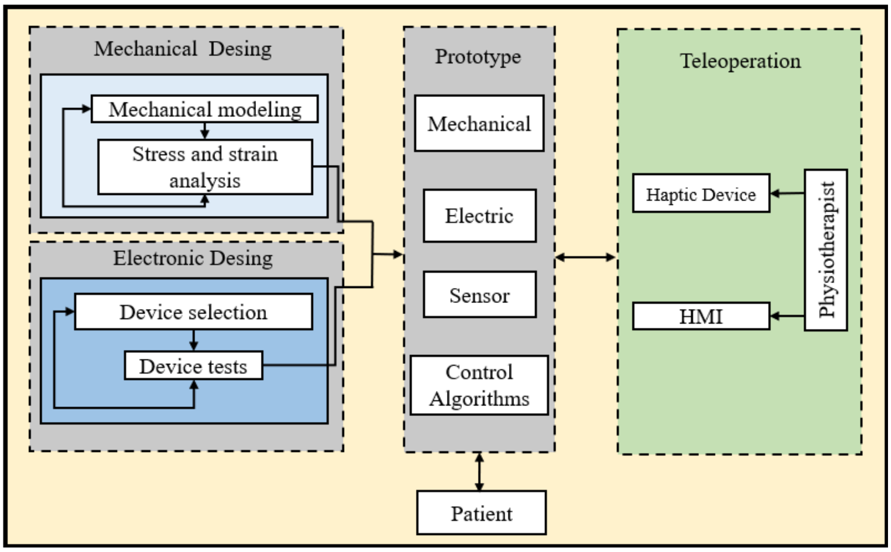


Fig. 1. Methodology for the implementation of the telerehabilitation system.

The proposed methodology consists of the following stages*: i) Mechanical design*, according to the anthropometric study, we propose the construction of a mechanism based on the connecting rod-crank system. The mechanical design was developed in SolidWorks software, with the purpose of designing and dimensioning each of the mechanical components. In addition, a finite element analysis of the mechanical design is performed using the same Solid Works software to determine the stresses and strains of the mechanical structure. *ii) electronic design*, in this stage, all the electronics implemented in the telerehabilitation system are defined. Mainly, the power supply stage, protection circuits, and DC/DC converters are considered, which allow powering each electronic component of the prototype built, *iii*) *Mechanical prototype*, prototype construction is based on mechanical design and electronic design. Therefore, the prototype consists of a mechanical part, electronics, sensors and control algorithms. Implementation of control algorithms will enable autonomous and teleoperated operation of rehabilitation routines. *iv) Teleoperation*, the telerehabilitation system considers a local station for the therapist and a remote station for the patient, interconnected through the Internet. The interaction of the therapist with the mechanism is through a haptic device with force feedback and a human-machine interface that allows controlling and monitoring the parameters of the built prototype and the patient.

Finally, the SUS system is used to measure the degree of usability of the system., which consists of a questionnaire consisting of ten questions, five of which were formulated negatively and the other five positively. [28].

3 Control Scheme

This section presents the control schemes proposed for this work. Two main schemes are considered, an autonomous control and a teleoperated control.

3.1 Autonomous control

Autonomous control means that the system is capable of operating in an environment, with or without the additional intervention of a human operator or any other external system, in accordance with the mission assigned [22] [23].

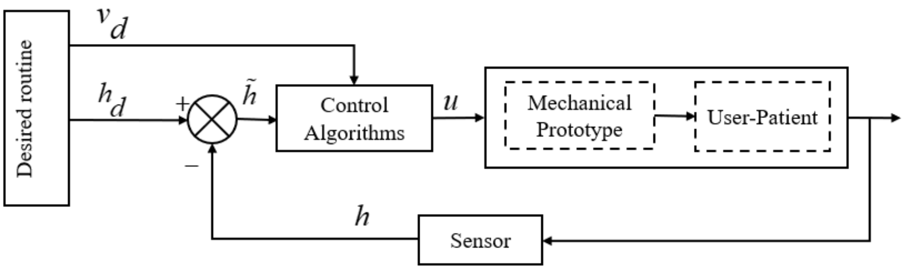


Fig. 2. Autonomous control of rehabilitation system.

For the autonomous control system, a closed loop control is considered, which is divided into three stages: *a) Desired routine*, where the physiotherapist defines the routine considering the degree of injury to the knee, in order to establish the flexion-extension displacement ranges; in addition to the speed and repeatability of the movements. These parameters are defined as: h_d to the flexion-extension motion profile; and v_d the speed of constant motion. The motion profile of the knee can be defined as: (see Fig.3).

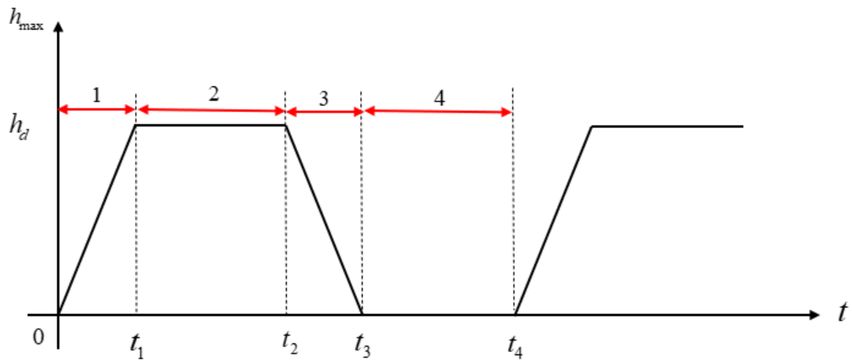


Fig. 3. Knee flexion-extension motion profile.

The proposed profile considers four main stages: 1) Extension, with a maximum of $0[rad]$, that is to say leg extended; 2) Extension pause, time interval in transition to flexion movement; 3) Flexion, greater than $\frac{\pi}{2}[rad]$ and reaches an average of $\frac{2\pi}{3}[rad]$; and 4) Flexion pause, time interval in the transition to the extension movement. In conclusion, the desired routine is defined as the knee displacement as a function of flexion and extension time.

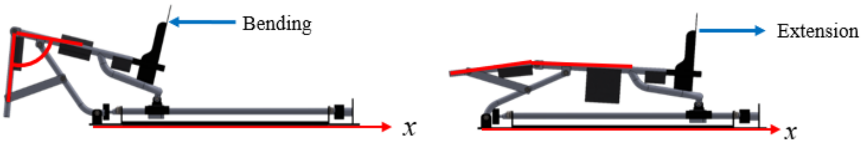


Fig 4. Bending angles $\left(\frac{2\pi}{3}[rad]\right)$ and extension $(0[rad])$.

Knee flexion and extension motion is developed according to the proposed motion profile. The maximum bending range has a reach of $\frac{2\pi}{3}[rad]$ and an extension of $0[rad]$ (see Fig 4). In addition, the motion profile shows a repetitive pattern over a time interval and is similar to a trapezoidal periodic function. Therefore, it is expressed by the equation (1).

$$h_d(t) = \begin{cases} \frac{h_d}{t_1} t, & if \quad 0 \le t < t_1 \\ h_d, & if \quad t_1 \le t_{pe} < t_2 \\ h_d \left(\frac{t_3 - t}{t_3 - t_2} \right), & if \quad t_2 \le t < t_3 \\ 0, & if \quad t_3 \le t_{pf} < t_4 \end{cases} \tag{1}$$

b) Control algorithms, where the movement profile for the execution of autonomous rehabilitation routines is received, consequently, the following control law is proposed:

$$u(t) = k_C \left[\tilde{h}(t) + \frac{1}{\tau_i} \int \tilde{h}(t)dt + \tau_d \frac{d}{dt} \tilde{h}(t) \right] + v_d(t) \quad (2)$$

where, $u(t)$ represents the control signal applied to the actuator; $\tilde{h}(t)$ is the angular position control error, is defined as $\tilde{h}(t) = h_d - h$, h_d corresponds to the desired value and h is the measured value of the controlled variable; k_c, τ_i and τ_d are the values of gain, proportional, integral time and derivative time, respectively, these values must be set appropriately to obtain optimum controller performance; $v_d(t)$ is the constant speed of movement used to improve trajectory tracking. Finally, *c) Human-Machine System,* where rehabilitation routines are performed through the interaction of the mechanical prototype and the patient. The system provides real-time motion feedback and correction.

3.2 Teleoperated control

The rehabilitation system operates in bilateral teleoperated control mode, when the therapist interacts directly with the patient to define the rehabilitation routines, without autonomous procedures [24] [22].

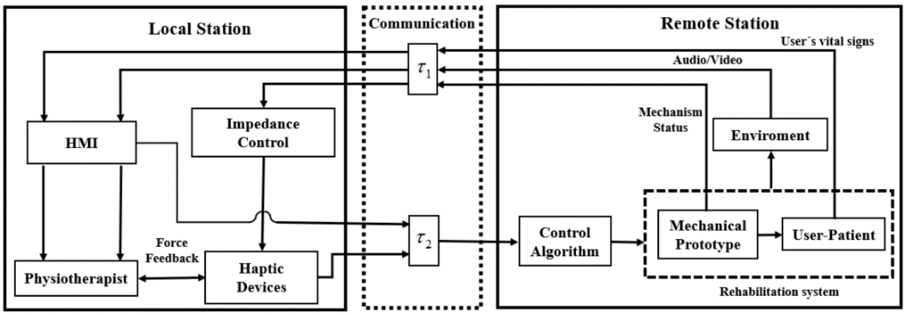


Fig. 5. Bilateral telerehabilitation scheme.

The bilateral telerehabilitation scheme allows the rehabilitation tasks to be managed remotely, as shown in the Fig. 2. The proposed control scheme is divided into three major sections: *i) Local station*, the therapist establishes the rehabilitation routine considering the degree of knee injury and the patient's vital signsTherefore, the operating parameters are the flexion-extension angular ranges, the speed of movement and the number of repetitions. The position data is generated through a haptic device, which provides feedback on the rehabilitation process the patient is undergoing. *ii) Remote station*, is mainly shaped by the interaction between the mechanical prototype and the patient. *iii) Communication channel,* is responsible for enabling bilateral communication between the local station and the remote station through the Internet. Time delays are considered where τ_1 and τ_2 are negligible. The communication considers mainly the sending of visual and auditory data, prototype status, biomedical signals, among others.

4 Experimental Results

This section presents the experimental results obtained. It is divided into two subsections: *i) Telerehabilitation system*, this section describes both the hardware and the software incorporated in the system; *ii) Rehabilitation routines* the results obtained by implementing various rehabilitation routines are presented. Finally, a usability analysis is carried out for the physiotherapists who operated the proposed telerehabilitation system.

4.1 Telerehabilitation System

The telerehabilitation system consists of a mechanical prototype, which describes both its mechanical design and the electronic components. In addition, it has a human-machine interface that allows the physiotherapist to configure the parameters of the rehabilitation routines, as well as to create a clinical history of the patient.

A. Mechanical prototype. This knee rehabilitator is based on several design requirements. From this information, an adjustable bar mechanism is modelled using CAD/CAE software (see Fig 6). It is essential to carry out a static analysis to determine the maximum loads acting on the mechanism and thus select the appropriate materials of construction.

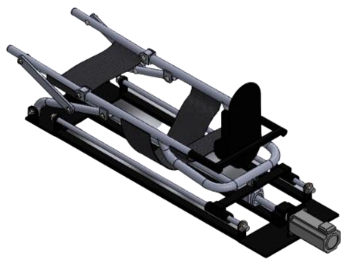
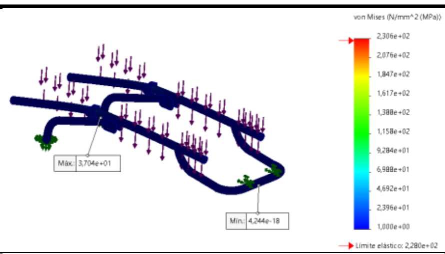
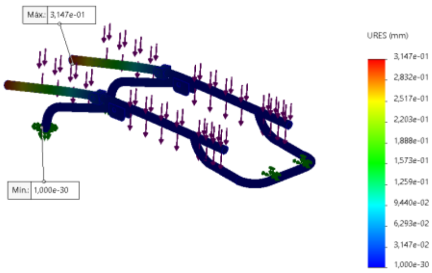
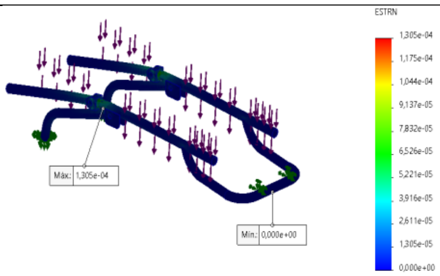


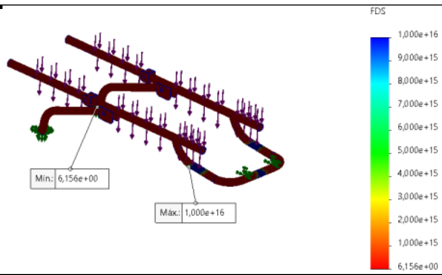
Fig 6. Mechanical prototype for knee rehabilitation.

The model of the rehabilitator structure is evaluated using the finite element method (FEM), which is a technique used to analyze the behavior of parts or assemblies [28]. This method is based on the discretization of the part into small finite elements, which are analyzed individually and then combined to obtain a global solution.

The basic steps to perform the structural analysis are as follows: *i) Preliminary stage*, involves defining the geometry, creating the meshing and setting characteristics to materials. For the rehabilitator, it is considered a carbon steel material ASTM A36; *ii) structural analysis,* the point forces previously determined by a force analysis are considered, considering the mass of the leg and gravity. For this particular case we consider the average weight of an adult Ecuadorian person, with a body mass index (BMI) of 30%, obtaining a mass of 100 Kg [29]. Finally, *iii) Final stage,* this analysis examines the upper and lower limits of the stress that the rehabilitator can withstand, in order to avoid exceeding its elastic limit. Static displacement, unit strain and factor of safety are also considered. The final results are shown in Table 1.

Table 1. Result of the rehabilitator's structural analysis.

Analysis Type	Rehabilitator's structure	Min. And Max. values
Nodal Tension		Max. Value 37.04 $[MPa]$ Min. Value $4.24e-18$ $[MPa]$
Static Displacement		Max. Value 0.317 $[mm]$ Min. Value 0 $[mm]$
Unitary Deformation		Max. Value $1.305e-4$ Min. Value 0

Analysis Type	Rehabilitator's structure	Min. And Max. values
Safety Factor		Max. Value $1.00e16$ Min. Value 6.156

During the analysis, a force of 177 [N] was applied. As a result, it is determined that the rehabilitator does not experience stresses that exceed its elastic limit. The maximum value of the displacement of the rehabilitator is 0.317 [mm]. In addition, it is observed that there is no unitary deformation. Finally, it is noted that the safety factor mechanically qualifies the device as safe.

B. Electronic design. The electronic diagram of the prototype is composed of the following stages: *i) The Power System*, consists of the home network, an AC/DC converter module, overcurrent protectors and DC/DC converter module. This stage is responsible for powering the different equipment and control elements considered in the rehabilitation system. *ii) Drivers Motor*, is an intermediary between the control unit and the motor, its main function is to provide the appropriate signal to the motor. *iii) Stepper motor*, coupled to an endless screw, with the objective of having a linear displacement. In addition, it is equipped with an encoder that allows the motor speed to be measured and fed back. *iv) Displacement reading*, made up of a Sharp distance sensor and an analog-digital converter, work together to perform displacement measurements in the rehabilitation system *v) Control Unit*, where closed-loop control algorithms are implemented to execute autonomous and/or teleoperated tasks. In addition, through the peripheral ports it is possible to connect audio and video devices in order to increase transparency when performing telerehabilitation routines (see Fig 7).

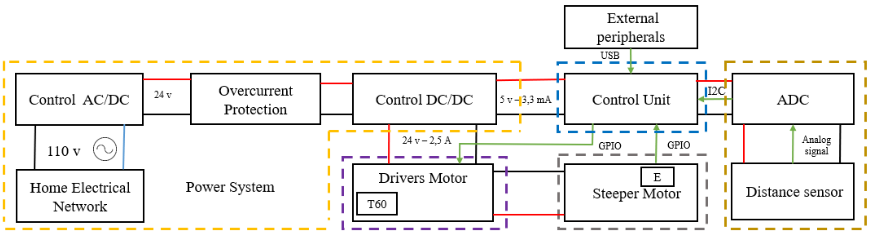


Fig 7. Electronic diagram of the rehabilitation prototype.

C. Graphical human-machine interface. Facilitates customized programming of rehabilitation routines. Therefore, the interface designed for the telerehabilitation system has two windows: startup window, configuration and monitoring window. The home window is responsible for recording and storing clinical histories with patient information containing personal data (name, age, sex, weight, height), type of injury and relevant remarks, as illustrated in the Fig 8.

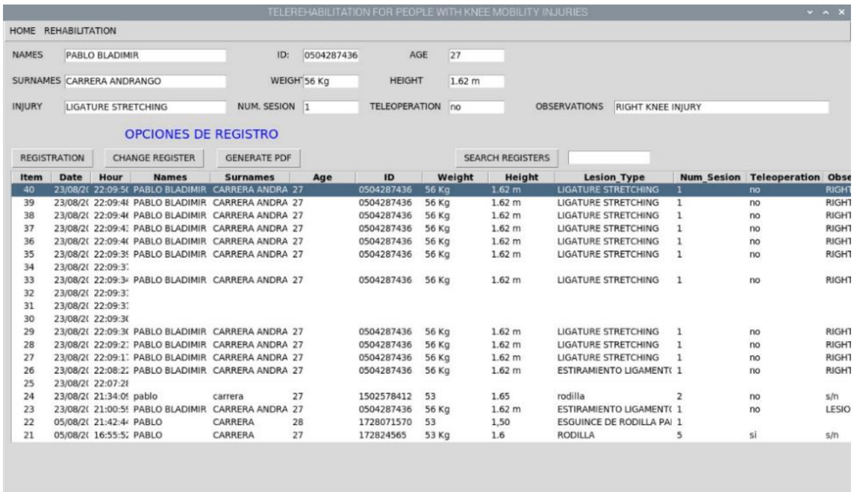


Fig 8. Start window: entering patient information and medical records.

In the rehabilitation window, the physiotherapist has the ability to customize the rehabilitation routine by adjusting the ranges of motion and speed according to the patient's clinical history. With regard to the routines generated through the haptic device, the physiotherapist must assess the type of injury the patient presents. It uses sensory and visual feedback to guide patients through flexion and extension movements (see Fig 9).

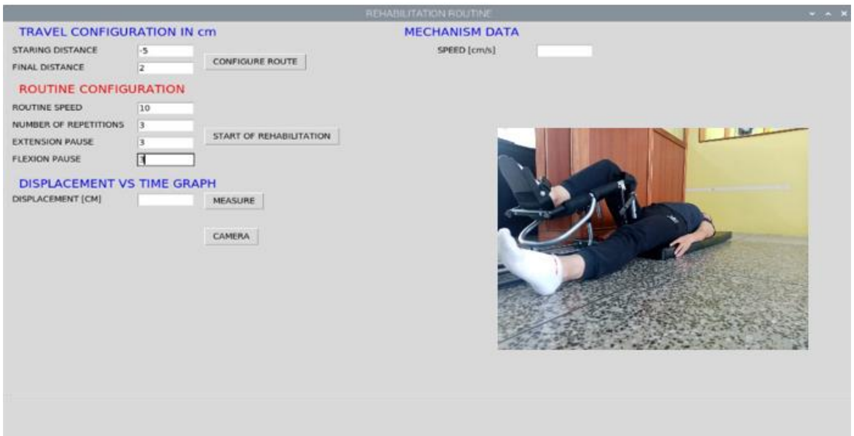


Fig 9. Rehabilitation window: defines the parameters of the rehabilitation routine.

4.2 Rehabilitation Routines.

Rehabilitation routines provide therapeutic movements planned and supervised by the physiotherapist, all remotely. In the telerehabilitation system, two types of routines are identified: *a) Predefined rehabilitation routines,* these are performed autonomously by the patient and programmed by the physiotherapist. and *b) Telerehabilitation routines,* in this modality, a direct interaction between the physiotherapist and the patient is established through the haptic device.

a) Predefined rehabilitation routines. the physiotherapist performs a series of movements exclusively using the human-machine interface located at the local station. The movement trajectories are carried out according to the patient's injury in accordance with medical criteria. The generated trajectory is shown as a trapezoidal wave (see Fig. 10).

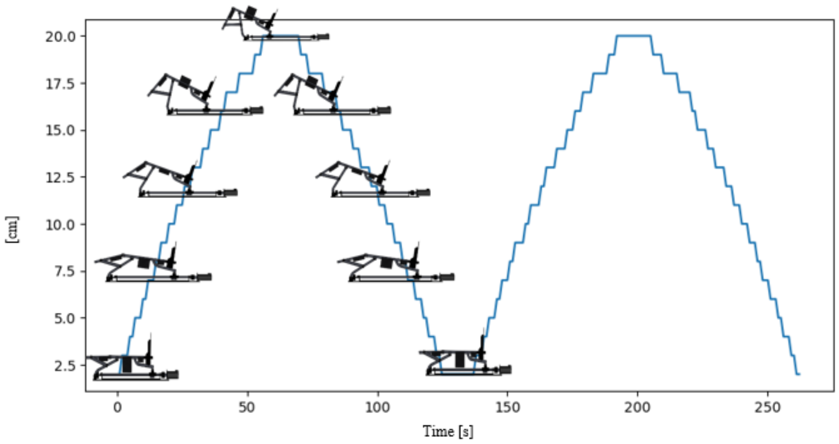


Fig. 10. Motion reconstruction based on real data. The generated graph is shown with small distortions due to the sampling time, which is 500ms, sufficient time according to the capacity of the microprocessor.

*b) Telerehabilitation routines***.** The rehabilitation routines are generated by a haptic device, in this case, the Novint Falcon. This device allows the physiotherapist to guide and control the patient's knee flexion and extension movements. During these routines, the physiotherapist receives force feedback provided by the haptic device to adjust the range of motion and sense the resistance generated in the patient's knee (see Fig. **11**). Importantly, the movement parameters can be recorded and stored for autonomous execution, which ensures greater transparency and precision in the operation of the teleoperated system.

Fig. 11. Motion control by haptic device.

The authors of the study provide training to five physiotherapists in order to familiarise them with the telerehabilitation system developed. This training was aimed at enabling therapists to understand the mode of operation and to acquire the skills necessary to use the system effectively. It is important to note that adjustments to speed, initial and final position are based on assessments and recommendations made by healthcare professionals and patient needs. In this study, an overall score of 80.56% on the System Usability Scale (SUS) was achieved, indicating a very satisfactory level of usability for the rehabilitation device.

5 Conclusions

In this work, a telerehabilitation system for people with knee mobility injuries was presented. For this purpose, the prototype was designed and evaluated using CAD/CAE software. The control scheme consists of an autonomous control, which allows the system to adjust to routines with predefined movements, i.e., without the constant intervention of the physiotherapist; and a teleoperated control, where the physiotherapist interacts directly with the patient using the Novit Falcon haptic device to define rehabilitation routines. The telerehabilitation system allows real-time communication between the physiotherapist and the patient, therefore, there is a close follow-up of the patient's evolution through the data collected during the remote rehabilitation sessions. Finally, the results obtained and the application of a usability test with 80.56% acceptance of the proposed telerehabilitation system were presented.

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