Biomechanical System Prototype with Advanced Biofeedback for Rehabilitation of Bedridden Patients

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Abstract: Citizens with physical limitations, namely bedridden patients, are often unable to perform physical activity alone, which can translate into long periods of immobilization, with serious consequences for their health. This type of patient usually stays in bed for long periods, leading to getting several motor problems due to their immobility. Thus, it is important to develop biomechanical systems that can be used in the implementation of physical rehabilitation activities for this type of patient. This work presents a prototype, specifically developed for bedridden patients, aiming to contribute to the prevention of complications associated with their immobility for long periods of time. The developed equipment is based on a modular structure allowing a linear module with active/passive operation and alternatively an active/passive rotary module, to perform different types of physical movements on upper and lower limbs. This work describes the developed management and control system with emphasis on the use of biofeedback sensors and real-time data analysis. The first tests carried out on the prototype clearly identified the benefits of the system when used in physical-motor rehabilitation procedures for long-term bedridden patients.

1 INTRODUCTION

The World Health Organization has set clear guidelines concerning sedentary behaviour, recommending that all citizens must have regular physical activity. However, in citizens with physical limitations, particularly in the case of bedridden patients, the capability of performing a physical activity is limited, which can translate into long periods of immobilization, with serious consequences for their health. This type of patient usually stays in bed for long periods, leading to getting several motor problems due to their immobility. Reductions in muscle mass, bone mineral density and physical impairment are the first evidence, associated with others that can appear, like muscular atrophy, muscular weakness, respiratory complications, blood circulation complications and bone demineralization (Parry and Puthucheary, 2015), (Parola et al., 2021) and (Campos et al., 2021).

The absence of muscular stimulation will affect the skeletal system (Eimori et al., 2016) and early mobilization is a key to increasing functional capacity and muscle strength in this type of patient, leading to significant outcomes (Miranda Rocha et al., 2017) and (Arias-Fernández et al., 2018). Thus, it is important to develop biomechanical systems that can be

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used in the implementation of physical rehabilitation activities, specifically for this type of patient. To develop and implement correctly this kind of device is necessary to have a properly defined physical rehabilitation program. Several programs have been defined by some authors, specifically for bedridden patients, like the works of (Akar et al., 2017) and (Maimaiti et al., 2019).

According to (Barandas et al., 2015) and (Condino et al., 2019) the implementation of real-time biofeedback systems is important for the effectiveness of rehabilitation plans, since there are a progressive growth in people's motivation and emotional involvement. (Barandas et al., 2015) even mentions that one of the reasons for the lack of adherence to the prescribed exercise program is precisely the lack of motivation.

During rehabilitation exercises sessions, it is important to monitor the patient's evolution and the patient's physical state. To do it, is required to have one or more equipment capable of monitoring the patient's vital signs and the forces that the patient can produce autonomously. The monitoring of vital signs can be performed through common medical equipment/devices. However, given the technological evolution, there are already commercialized devices that allow monitoring some of the most important vital signs, in a practical and fast way. Moreover, the measurement of forces produced by the patient during the exercises, allows the clinics to better judge the patient rehabilitation. In addition, measurement history allows for better evaluation and fine-tuning of rehabilitation exercises. Another important aspect of measuring the forces applied/suffered by the patient is the possibility of automatically adjust the exercises and limiting the amplitude of movements to the patient's condition.

The work presented has its context in the project ABLEFIT, which aims to contribute to the development of methodologies and systems that ensure physical activity for this type of patient. This project focuses on the development of physical rehabilitation equipment for bedridden patients, that can contribute to the prevention of complications associated with their immobility for long periods. The developed equipment involves a structural support and positioning unit, a set of actuators with biofeedback sensors, and a control, monitoring and gamification unit, with user interface. In the following chapters, the design and development of this mechatronic physical rehabilitation system and its user interface are addressed.

2 THE ABLEFIT PROJECT

The ABLEFIT project comprises the research and development of an advanced physical rehabilitation system for bedridden patients with prolonged immobility, capable of:

- Prevent complications associated with immobility in bed;
- Increase the functional capacity of the musculoskeletal, cardiac and respiratory systems;
- Promote the integration of physical exercise programs suited to the clinical condition of each patient;
- Improve the patient's quality of life.

The equipment should have an advanced control system to monitor several parameters related to both the patient and the performed exercise, especially taking into account the speed and strength performed by the patient, or imposed by the equipment. This will allow to record and evaluate the patient's progress and performance. This registration, together with the implementation of a future gamification solution, are two extremely important factors when it comes to patient motivation. Gamification serves as a stimulus for the user to practice certain exercises. The existence of a record that allows users to understand their evolution throughout the rehabilitation period encourages them not to give up on the process, which can be an important factor in the efficiency/effectiveness of the exercises. Real-time biofeedback systems are extremely important for the effectiveness of rehabilitation plans, as there is a progressive increase in people's motivation and emotional involvement.

Regarding the physical-motor rehabilitation component, the equipment must have the ability to perform a set of exercises that guarantee results for patients. The base system was thus defined for mobilization requirements with flexion, extension, abduction and adduction of both upper and lower limbs.

2.1 The Prototype

Some of the most common exercise equipment focuses on one type of movement. This is the case of stationary bicycles where circular movements are performed or rowing simulation machines with linear movements. The prototype concept brings together both types of movement, and is based on two complementary modules:

- Linear module for the implementation of linear movements with a curvilinear trajectory of the upper and lower limbs;

- Rotating module for the implementation of circular movements of the upper and lower limbs.

For the intended modularity, a support structure was developed, with a fitting system for replacing the modules and vertical tuning, which allows adjustment to the adequate and safe interface with the patient. The C-shaped system allows adjustment to the bed where the patient is. Figure 1 shows a view of the system and its interface that fits to a hospital bed. The support structure, in addition to guaranteeing the stability of the modules/interfaces, allows adjustment and fitting in any bed where a patient lies.

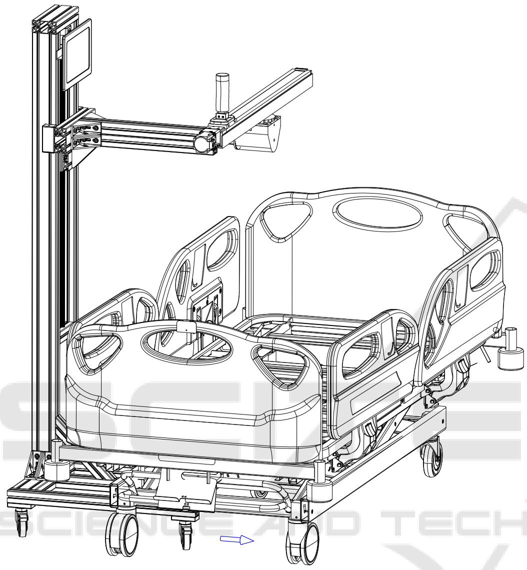

Figure 1: ABLEFIT prototype 3D system visualization next to an hospital bed.

Figure 2 presents a 3D representation of the system with the integrated tablet for visualization / monitorization and the rotary and linear modules, that are interchangeable, according to the pretended exercises. This 3D visualization allows an understanding of the concept developed and presented in the prototype.

2.1.1 Linear Module

The linear module is based on a linear guide unit that presents a maximum speed of 420 mm/s, a push force of 400 N and a stroke of 800 mm, which guarantees the required levels of force, speed and range of motion for usage in rehabilitation. This linear guide also includes an absolute encoder enabling a precise and safe positioning/motion even at startup. This type of actuator allows its control both in terms of velocity and position, guaranteeing the implementation of the system both in an active system line and as a passive system. The user interface handle is fixed to the sliding base of the linear guide. This interface (Figure 3) includes the motor carriage connection base, a perpendicular recessed load cell to the carriage for force measurement, which allows quantifying the force applied in both directions of the linear movement, and an ergonomic external structure for gripping the patient hand (handle). At the top of the load cell beam, with a snap-on/disengage system, there is a clip-on pedal fitting system, which allows the coupling of a safety hinged boot (walker), thus ensuring the use of the linear system with the lower limbs, providing leg support.

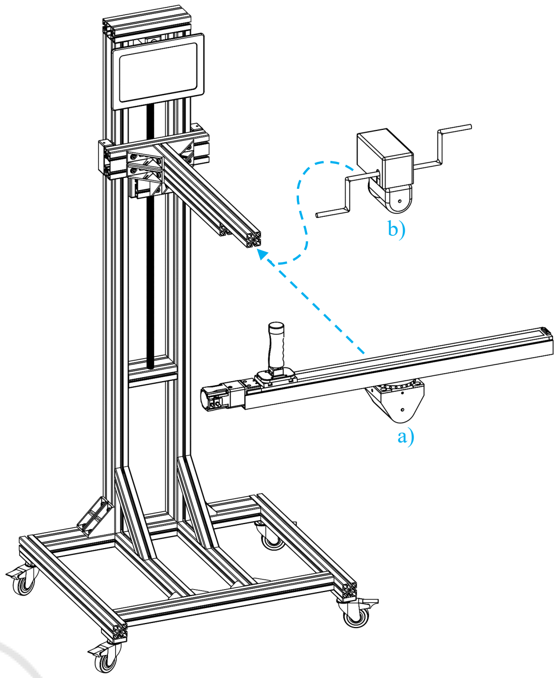

Figure 2: 3D system visualization of the prototype with the interchangeable rotary and linear components.

Figure 3: Linear module connection to an adapted hinged walking boot.

2.1.2 Rotary Module

The rotary module involves the use of a DC motor with reduction gearbox, fixed to a mechanical frame support connector component, which is attached to the vertical adjustable, interchangeable end of the structure. The rotary motor system also guarantees the use of the system in both an active and passive system line, providing enough force and speed. This engine together with the selected gearbox allows a maximum speed of 223 rpm, and allows the execution of a nominal torque of 297.1 Ncm.

The hand handler interface is shown in Figure 4, and it allows rotation around the shaft. This grip can be replaced by another one with a pedal strap, as described for the linear system, where the boot and strap are fitted for use with the lower limbs.

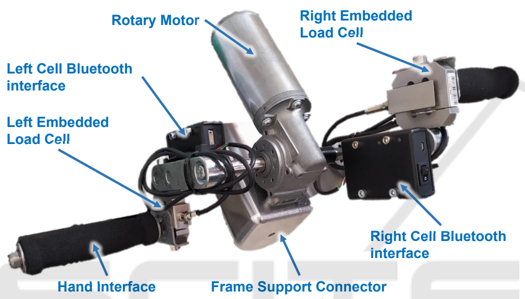

Figure 4: Rotary module constitution.

2.2 Management and Control System

Figure 5 presents the complete system, that is composed of:

- Sensors to provide the biofeedback, including the measurement of the applied forces, velocity and/or cadence and vital signals;
- Tablet/monitor to be used as interface with the clinic for parameterization or to be used as gamification visualizer, to encourage the patient;
- The actuators for the linear or rotary movements, as previously described;
- Database to keep all the patients exercises plans and relevant data information. The exercises data include the measured forces, vital signals and duration of exercise, allowing to create automatic reports that can be locally or remotely accessed or automatically sent to the clinics;
- Microcontroller that acts as the brain of the all the system, interconnecting all the previous components.

This section pretends to better describe each of the enumerated components. The database is in development and will be better explained in future works.

2.2.1 Sensors

To provide a complete biofeedback to the clinics and to allow the system to better adjust to the limits of the patient, multiple sensors are required.

The main quantity to measure on rehabilitation movements is the applied force on the contact point between the patient and the system. Also, the vital signs should be evaluated previously, during and by the end of the exercises.

Sensors on Linear Module

Since the linear module actuator already provides the position information of the carriage allowing the calculation of the velocity of the movement, the only extra required quantification is the force applied by the system to the patient (the system is forcing the movement) or by the patient to the interface (system acts as load). To measure this force, two distinct versions were developed:

1. The first experimental sensor setup designed for this task consisted on a matrix of 4 load cells (FX29 Compact Compression Load Cell, from TE Connectivity), shown in Figure 6. The used cells had a range of 250 N with an amplified output that can be directly interfaced to the system microcontroller ADC. This handle configuration approach enables to measure if the patient is twisting the handle while pooling or pushing it. The four cells setup could also be used to measure the handgrip strength with a handle designed for this effect. This prototype setup, in mechanical terms, turned out to be complex to adjust and calibrate.
2. The second sensor setup uses only one flexural load cell, as shown in Figure 7. This sensor is able to measure only the forces on the direction of the movement of the linear system, allowing to evaluate the direction of the applied force. The used sensor was an AnyLoad load cell, model 108BA, with an analog mV output, that must be connected to the main microcontroller through a specific electronic load cell amplifier module. The main disadvantage of the usage of this cell is the noise interference susceptibility, that could result in erroneous measurements.

At the end, the chosen force measurement version was the flexural load cell, mainly because it allows a simpler and more robust assembly and fixation. Also, with this load cell is easier to adapt the clip-on pedal fitting system to be used with the lower limbs (see Figure 3).

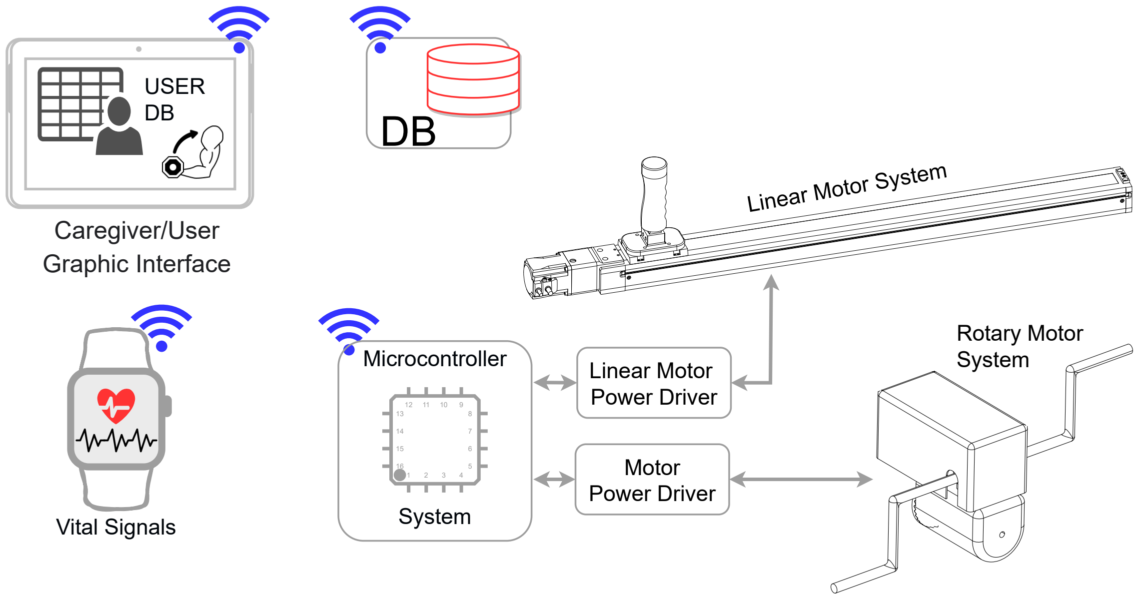

Figure 5: ABLEFIT Functional Diagram.

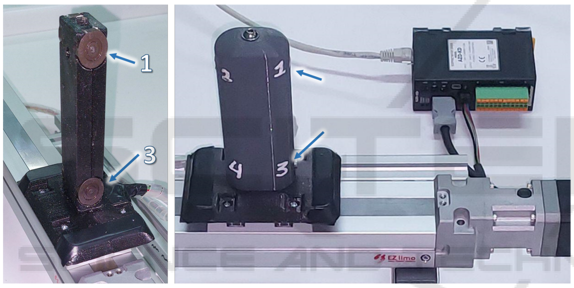

Figure 6: Force feedback acquisition with 4 load cells.

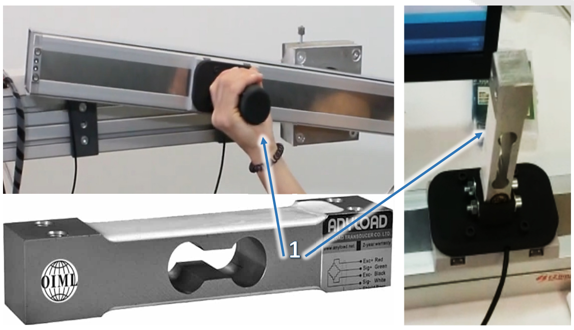

Figure 7: Force feedback acquisition with a flexural load cell.

Sensors on Rotary Module

For rotary movements, its required to quantify the forces applied on left and right hand/foot interfaces and the cadence. The characteristic of the movement on this module, requires the measuring device to be cable free, i.e., it is impossible to have cables attaching the measuring device to the main microcontroller. This resulted on the development of a self-powered device with Bluetooth wireless communication, that is replicated in each side.

The measure of the force is carried throw an S-type load cell that is attached to the lateral rotation shaft, allowing the quantification of the force exerted by the arm or feet (see Figure 4. This load cell interfaces with a low-power microcontroller in a similar way as described for the flexural load cell applied to the linear module.

For the cadence quantification, an Inertial Measurement Unit (IMU) can be used, tacking advance of the embedded gyroscope.

Regarding this device is battery powered, special attention was carried on power consumption. A low consumption microcontroller from Nordic Semiconductor was chosen, providing a Bluetooth Low Energy (BLE) interface for the communication with the main microcontroller.

Sensors for Vital Signals

A survey of all vital signs that would be important to measure during rehabilitation sessions was carried out. The vital signs considered to be most relevant and that can be evaluated using COTS wearable devices are the following:

- Heart Rate;
- Blood Pressure;
- Peripheral Oxygen Saturation;
- Respiratory Frequency;
- Body Temperature.

A preliminary analysis of available devices, with open SDK and Bluetooth interface, was already carried and will be integrated in the nearby future.

2.2.2 Actuators

As mentioned before, the described system allows the patient to make exercises using a linear module for curvilinear movements and a rotary module for circular movements, both providing the coupling of upper or lower limbs. These actuators are exchangeable and only one is connected at a time.

The chosen linear guide was the EZS6-D080-AZAKD from OrientalMotor company. This actuator have a specific controller unit that can be interfaced with the main microcontroller using ModBus RTU Protocol. This actuator controller enables to set the maximum acting force when used in active/passive modes.

For the rotary movement, a permanent magnet DC motor with reduction gearbox from Dunkermotoren company was chosen. The speed and force control for this motor is carried through a common motor power driver interfaced with the main microcontroller.

The supply voltage for both actuators is 24V, hell suited to be directly supplied by a regulated battery module, allowing safe standalone off-grid operation.

2.2.3 Tablet/Monitor

Fixed to the main structure of the prototype (see Figure 2) is an Android based tablet used for interaction with both the patient and the clinic professionals.

For the clinic, the tablet is used to configure all the system so that it respects the physical limits of the patient. The developed application has access to the patient personal data and the respective list of prescribed exercises. It also allows to access the history of exercises which includes the data from biofeedback sensors. This feature permits to obtain an historical assessment of the patient condition over time.

Figure 8 shows a work in progress application. Left picture is a screen capture of the parameterization of the exercise. The right picture shows and real-time graph of the measured force.

Another usage of the tablet is the gamification and encouragement of the patient. This feature is under development at the moment, and the idea is to encourage and motivate the patient to realize the exercise. For example, if the exercise is a rotational movement with lower limbs, similar to cycling, then the tablet could show a road with moving scenario to give the idea of movement. Additionally, to motivate the patient to apply more force, some virtual cyclists could be added, running at the similar speed, so that the patient try to overtaken them.

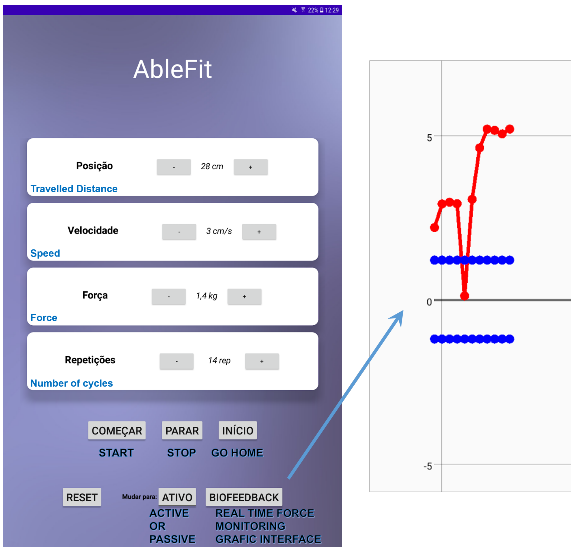

Figure 8: ABLEFIT Android APP.

2.2.4 Main Microcontroller

The main element of the electronic control system is the microcontroller, that receives the set-point definitions for the exercise, the information from the all the sensors, and controls the actuation of the connected module, either the linear or the rotary actuators.

The microcontroller chosen was an ESP32 that already integrates a BLE and Wi-Fi interfaces, providing all the required wired and wireless communication with the previously present components.

The retrieved information from the attached actuator, is forwarded to the tablet and also internally used in a classic closed loop fashion control, taking care that the patient never exceed it's own physical limitation, as initially configured by the clinic professional, for the sake of security.

3 EXPERIMENTAL TESTS

The prototype first tests were implemented to identify possible exercises functionalities, having been carried out under supervision of health professionals.

Figure 9 shows examples of performing exercises with the rotary module and Figure 10 shows examples of performing exercises with the linear module.

The preliminary tests showed that extension and flexion movements were full performed in active and passive modes. This special feature allows the prototype to be used for rehabilitation of patients that can

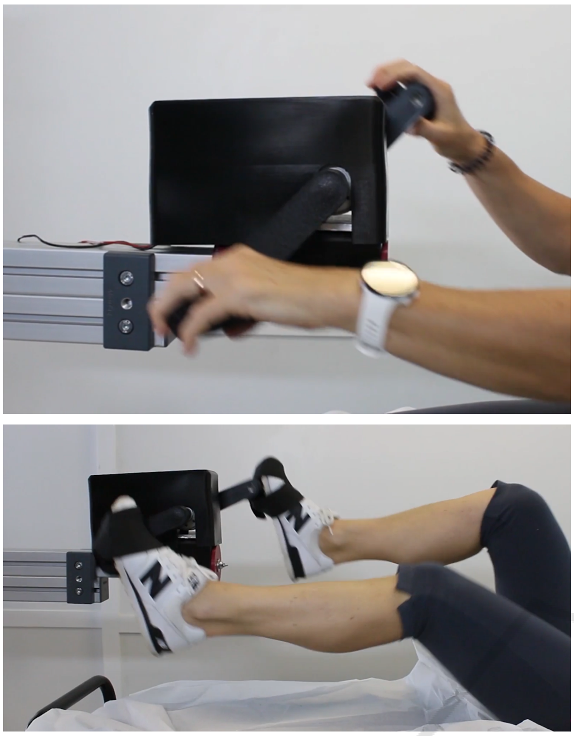

Figure 9: Examples of experimental tests with the rotary module.

produce movement, and also the rehabilitation of patients that have loosed all the muscular activity.

4 CONCLUSIONS

This work present the design of a biomechanical prototype equipment for the accomplishment of physical rehabilitation exercise by bedridden patients. The developed system allows the realization of a specific set of exercises, considered relevant for this type of patient. The system incorporates a linear module and a rotation module, that are interchangeable. Both modules can be used in active or passive modes, fully configurable and customized, safeguarding the physical limitations of the patient.

The developed management and control system is able to collect information from biofeedback sensors and correctly control the actuators movement according to the prescribed exercise. An Android based tablet is used to motivate the patient through gamification, and is also used by the clinic to configure the exercises, to visualize real-time data or to access historical patient information.

Preliminary tests performed by health professionals showed the mechatronics prototype robustness, evidencing an excellent adjustment and positioning capability, fulfilling the function of interfacing with the patient in hospital beds, enhancing the realization of upper and lower limb exercises.

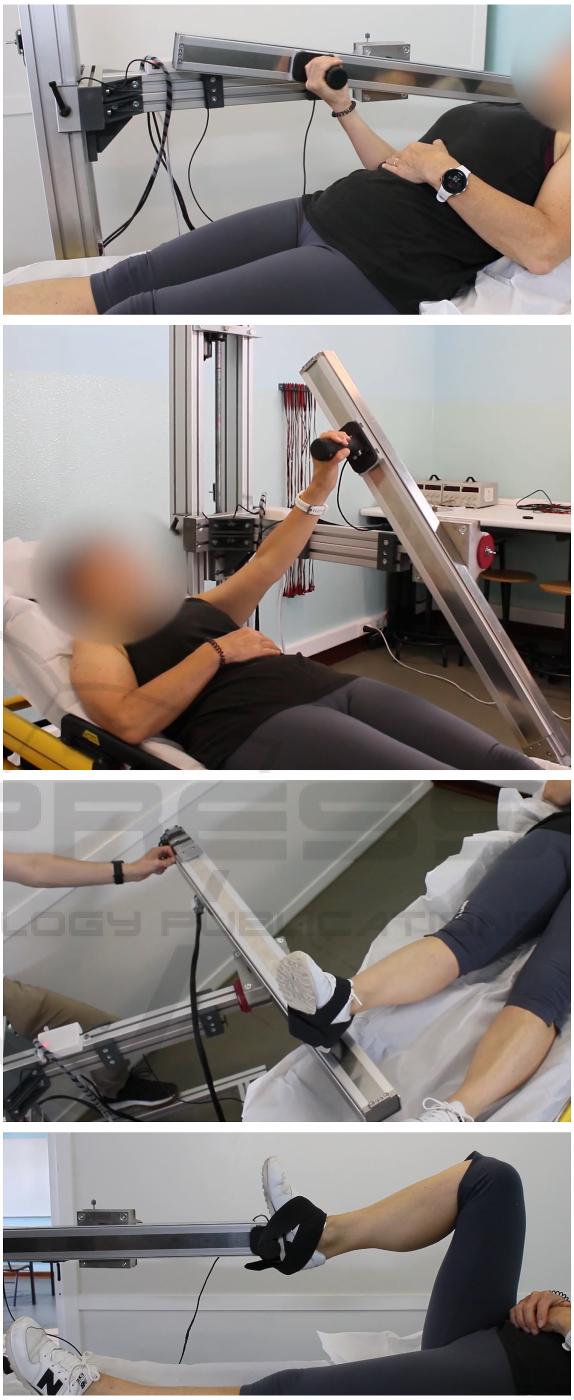

Figure 10: Examples of experimental tests with the linear module.

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