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INNOVATIVE DEVELOPMENT OF A PARALLEL ROBOTIC SYSTEM FOR LOWER LIMB REHABILITATION

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Abstract: *This paper proposes a parallel rehabilitation robotic system, for lower limb medical rehabilitation, targeting especially post-stroke patients with motor function impairments. The paper presents the experimental model development, highlighting the main components of a solid and reliable mechanical structure, complying with the medical requirements. The control system has been developed using microcontrollers and a user interface which shows a real-time robot configuration simulation of the robot during training exercises is also presented.*

Key words: *parallel mechanism, rehabilitation, lower limb, modeling, control.*

1. INTRODUCTION

Robot assisted therapy research has gradually progressed and there has been a large increase in the numbers of therapeutic robots in the last two decades. Robotic rehabilitation therapy may include high-dose and intensive training in neurological diseases (I.e., stroke, spinal injuries) [1]. From a neuromuscular perspective, interactive bio-feedback means that assistance or resistance is precisely controlled during the exercise, good repeatability is achieved and good training encouragement is given [2].

Some important examples of mechanized systems used in human limb rehabilitation are orthotic systems [3-4], exoskeletons [5], or robotic structures [6-7]. These systems have been increasingly used in recent years to rehabilitate human gait or to move injured human joints.

Several stationary training systems have been developed, targeting the rehabilitation of the lower limb from a sitting (supine) position. Most of these systems [8-9] have a serial architecture, which lead to a relatively large and cumbersome mechanical structure. Others [10], although very simple and lightweight, don't offer enough control at the level of the main joints of the lower limb, thus limiting the training capabilities to only a few exercises or motions. **RECOVER** [11-17], the parallel robotic system presented in this paper, targets the lower limb and provides a simple architecture able to achieve both the gait training as well as other different exercises, specific for each individual joint: hip flexion/extension, knee flexion, ankle flexion/extension and eversion/inversion. The robotic system consists of two parallel modules, which can operate simultaneously or independently of each other. The first module designated for hip and knee joints rehabilitation is designed to help in rehabilitation training of the following motions: hip flexion/extension, knee flexion. The second module is designed for the rehabilitation of ankle joint and is able to perform training motions as flexion/dorsiflexion a plantar eversion/inversion. Each parallel module has 2 DOF with the active joints q1 and q_2 for hip-knee module as is shown in Figure 1 and q_3 and q_4 for ankle module as is shown in Figure 2. Each module has three kinematic chains. The kinematic chains of hip-knee (Figure 1) module are:

(1) is a RR linkage having 2 passive joints, namely the R_h (hip joint), R_k (knee joint) revolute joints and the L_f, L_t links corresponding with femoral and tibia sides of the lower limb.

(2) and (3) are two identical PRR kinematic chains. These chains are actuated by q_1 and q_2

respectively, having also the revolute joint R1 and link l_1, respectively the revolute joint R_2 and link l_2. Both chains are intersected in revolute joint R_3 where is also the origin of O'X'Y'Z' that is the origin of moving frame.

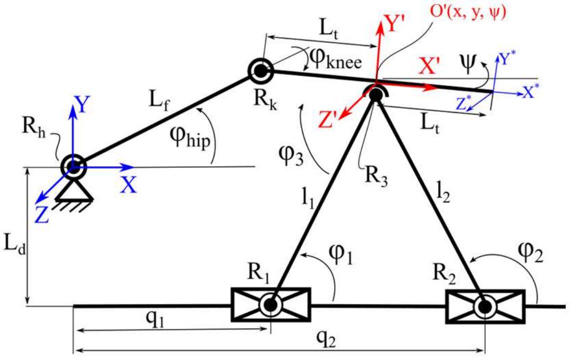


Fig.1. The kinematic scheme of hi-knee module [13]

The ankle-module (Figure 2) kinematic chains are defined as follows:

(4) is RR type having revolute joints R_{a1} and R_{a2} with free rotation having orthogonal axes (which intersects the origin of both fixed and moving coordinate frames) The chain supports the sole of the patients in a manner that should connect the ankle rotation axes with the axes of Ra1, Ra2. The distance ls is adjustable to account for anthropomorphic variations.

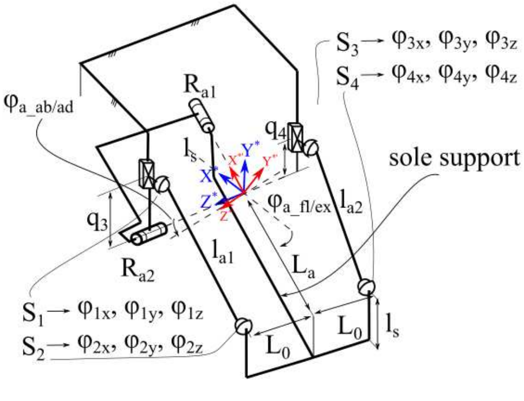


Fig.2. The ankle module kinematic scheme [13]

(4) and (5) are two identical PSS input chains, symmetrically assembled having reference the X*Y* plane. (4) begins at a distance of L_0 in the direction of Z* ($-L_0$ for (5)), is actuated by q3 in the direction of-X* (q_4 for (5)), and has the relation l_{a1} between the two spherical joints S_1, S_{22} (l_{a2} is placed between S_3 and S_4 for (5)). The spherical joints S_1 and S_3 are connected to the active joints q_3 and q_4 respectively, while the mobile platform is connected to S_2, S_4.

In the following, the paper presents the RECOVER experimental model (section 2), the control system ready for initial validation tests (section 3) and some conclusions and future work (section 4).

2. RECOVER EXPERIMENTAL MODEL

To test and validate the previous research activities related to the development of RECOVER and to assess the rehabilitation capabilities to perform the proposed rehabilitation medical tasks, the experimental model has been developed. The robot frame consists of a long table (support) presented in Figure 3, having a length of 2000mm, built from rectangular 60x30x3 steel profiles, yielding a strong reliable and stable base.

Fig.3. The RECOVER support frame

The active **hip-knee module** joints are positioned on the table and are actuated by two Nema23 stepper motors which are shown in Figure 4, each of them having a torque of 2Nm, which is more than enough to drive the q1 and q2 joints along the OY axis.

A 16 mm diameter ball screws and a 5 mm pitch achieve the linear motions of active joints (q_1 and q_2), the ball nuts are attached to linear blocks that easily slides on rail guides, so the translation would be smooth (Figure 5).

The stroke of q_1 is 950 mm and the stroke of q_2 1550 mm. All rotation joints are equipped with a set of radial bearings. The mechanical links are made from Al alloy (AW 6082) square pipes (40x40x2). In order to accommodate a range of human lower limb sizes, the L_f and L_t links are adjustable. To provide good and comfortable support for the human lower limb, the thigh and lower leg supports are ergonomically made.

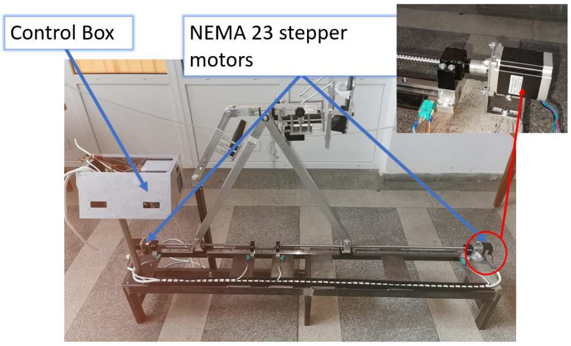


Fig.4. The positions of stepper motors of hip-knee module

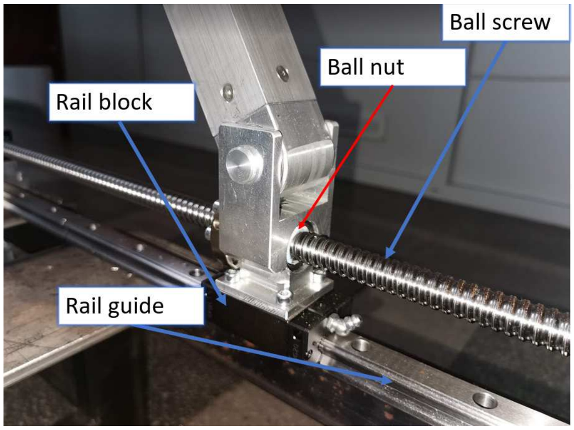


Fig.5. Ball screw mechanism

The ***ankle module*** is a parallel mechanism built from aluminum alloy, it is fixed on the lower leg support and helps in rehabilitation training of ankle joint. The active joints are actuated by two stepper motors NEMA 17 that are presented in the Figure 7, having 1Nm torque. Translation of the active joints is carried out by means of a trapezoidal nut screw mechanism having a diameter of 10 mm and a pitch of 2 mm.

Two linear bearings (SC8UU) that are fastened by the trapezoidal nuts allow the translation of the active torques. For the kinematic chains PSS type, are used (4) M6 commercial spherical joints (S_1, S_2, S_3, S_4). The passive rotation joints Ra1 and R_{a2} necessary to perform eversion/ inversion and flexion/dorsiflexion of the ankle joint are equipped with radial bearings. Figure 8 presents a training position of RECOVER with a human lower limb placed on the limb support of the robot.

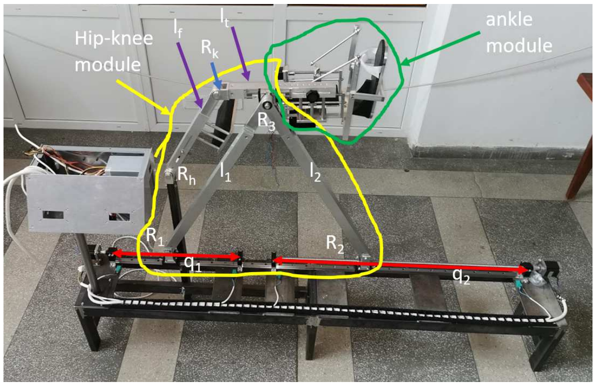


Fig.6. The main kinematic elements of hip-knee module

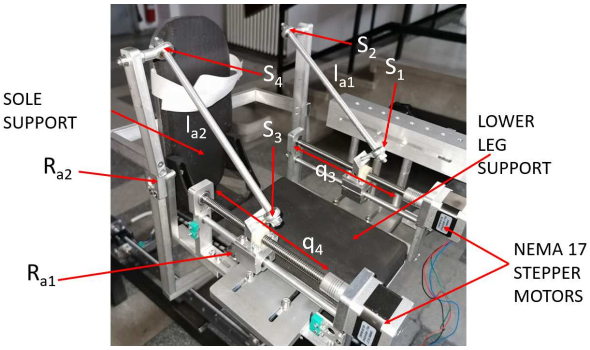


Fig.7. The ankle module experimental model

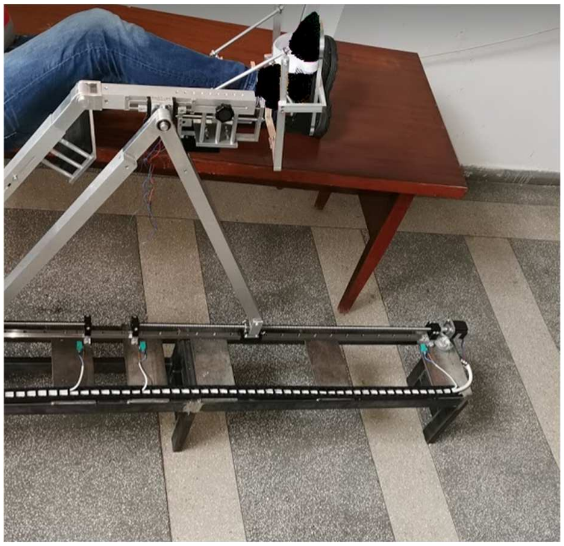


Fig.8. RECOVER with a lower limb placed in training position

3. THE CONTROL SYSTEM OF RECOVER

The control architecture (diagram) of RECOVER is presented in Figure 9, consisting of three levels, namely: user level, command and control level and physical level.

The **User Level** consists in the user interface, a PC which hosts the graphical user interface (GUI), at the moment in the testing stage (Figure 10). The inputs into the robotic system can be achieved using the GUI or a 4-buttons micro-keyboard which facilitates the selection of the desired motor that is driven forward or backwards as long as the specific key is pressed. An LCD display that also controls the selection and storage of the working speed of each motor enables the selection of the desired motor.

The **Command and Control Level** consists of an “Arduino Uno” board with an ATMega328P microcontroller (or Arduino Pro microcontroller with an ATmega32U4) operating at a frequency of 16 MHz, generating a control signal through a TB6600 driver to operate each individual motor.

The **Physical Level** consists of the mechanical structure and external sensors.

The microcontroller signal is a symmetrical rectangular signal that is generated by changing the voltage level of one pin of the module at equal intervals caused by a delay of 1sec while waiting for the microcontroller to perform no useful action. The desired command can be rendered on the PC link line on its USB interface. The next step is to create a specific control algorithm to drive the robot motors for this, the development of a computer program was initiated, visualizing the robot structure, using as input the manual commands provided from a virtual keyboard (buttons on the GUI).

The test interface has been developed in Visual Basic and simulates the robot motions on the screen, the "hip-knee-sole" positioning of the leg of the patient lying on the corresponding robot table and carried out by the fixed part of the robot, as well as the control and visualization of the sole rotation movements (the Ankle Module) provided by the two motors and the moving part of the mechanism (the sole). The software controls the robot's movements from a virtual keyboard, by clicking the key corresponding to the desired action with the "mouse" or by pressing a particular key on the PC physical keyboard. The corresponding motor can rotate forward or backwards as long as the desired key is pressed and the robot's simulated trajectory and the reconfigured architecture of the robot. The strokes limits are controlled both within the control system (imposing mathematical limits) as well as using sensors on each motion axis. Snap-Action Switched sensors have been mounted at the end of each rail guide, being used both as stroke limiter as well as for initialization purposes (homing process).

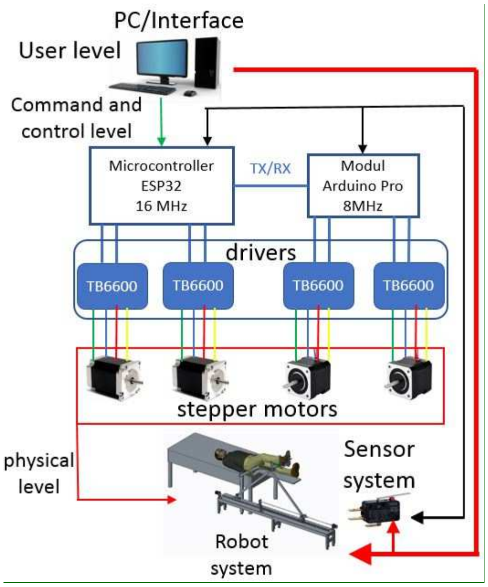
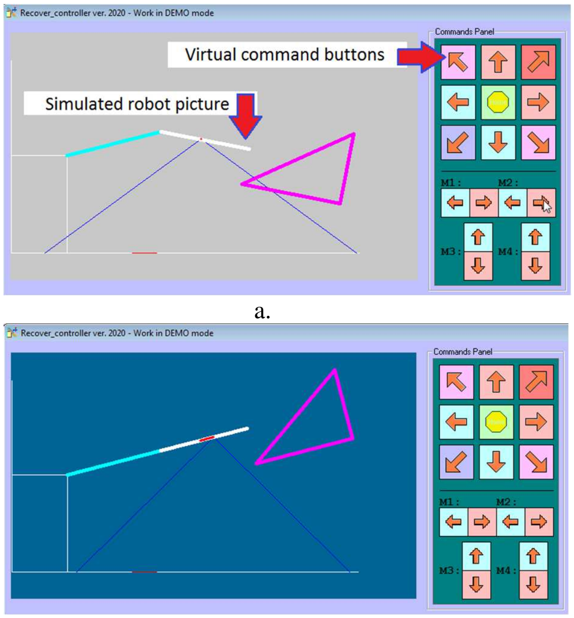


Fig.9. The RECOVER control system architecture

The simple individual commands, both back and forth for the analysis, were complemented by the development of two separate control algorithms. The first control algorithm allows the robot to lift or lower the patient's knee to the desired position while continuously preserving the angle between the femur and the tibia during movement, while the second algorithm manages the same femur-tibia angle by keeping the knee in the same fixed position. The two commands are rendered with two pairs of virtual buttons similar to those for basic activity and are likely to be useful when designing a complex movement scenario for training. Based on the principles from [18] Figure 10 captures the execution of the simulation program, showing two different configurations of robot.



a.

b.

Fig.10. The testing interface of RECOVER, showing different configurations of the robot during training exercising (a. and b.)

The next step in the development of the control system of the robot was to redesign the hardware interface to make it possible to control the four motors of the robot simultaneously. Furthermore, the hardware interface must continuously track the important positions of the robot, this feature being completely ignored at the initial development stage.

The simultaneous control of all motors can be solved reasonably easy by implementing the commands in the interrupt routine created by the microcontroller timer every 20 microseconds of the Arduino module so that each motor can be independently controlled in terms of speed and direction of rotation. Because the TB6600 driver modules also have a control to authorize the operation of the motors, namely the "Enable" signal, the number of digital commands of the robot becomes too large (4 motors x 3 control signals + 2 serial communication signals for command and control from the computer + 2 LCD display control signals + 4 manual "keyboard" implementation signals), which makes it impossible for the initial Arduino board to control all the required signals due to its hardware limitations (the lack of input/output pins). Furthermore, because the robot motors are positioned at considerable distances from each other and from the power supply, it is difficult to interconnect the modules on both the power side (12V power supply and current consumed substantially in the order of 5-10 A) and the digital control component.

Due to all these reasons, the control system of RECOVER has been reconsidered in such a way that the robot control is divided between two microcontroller modules, thus including an ESP32 WROOM module. This high-performance and programmable module, similar to the classic Arduino modules, take control signals from the device via its serial line on the USB link. The commands to the robot can be provided in this way with the internally implemented module and Bluetooth receiver/transmitter, the control can be taken from a SMART phone with special software created for this mode of wireless communication. This solution has been selected as the default control mode if the command is generated by the telephone or PC (standard serial Bluetooth communication or BLE on the internal interface or "USB Bluetooth dongle"). The ESP32 module will also produce motor control signals for motors m1 and m2 (hip-knee module) mounted on the fixed side of the robot, ensuring the positioning of the patient's knee and the patient's ankle mechanism. This mobile part of the robot supports m3 and m4 motors controlled by a second lower-performance Arduino module, the "Arduino Pro Mini - The Simple" modified to function at a low voltage of 3.3 V, just as the ESP32 module, but at a low frequency for this purpose at 8 MHz, connected to the first ESP32 module through the standard serial line. This division of signal loads makes the control pins adequate for the control and command of all robot motors, needing just two wires to supply the 12 V moving component and two wires for the contact between the two modules. The block diagram of the hardware interface is shown in the Figure 11.

The simulation software has been modified to send the control commands of the robot motors to the PC serial port [19],[20] parallel to the simulation initially carried out, which is currently being tested for both wired and wireless communication. The ESP32 microcontroller has a firmware similar to the one implemented on the initial interface with Arduino, each motor being controlled from the micro keyboard attached to the module in the same sequential manner even if now the motors can run simultaneously.

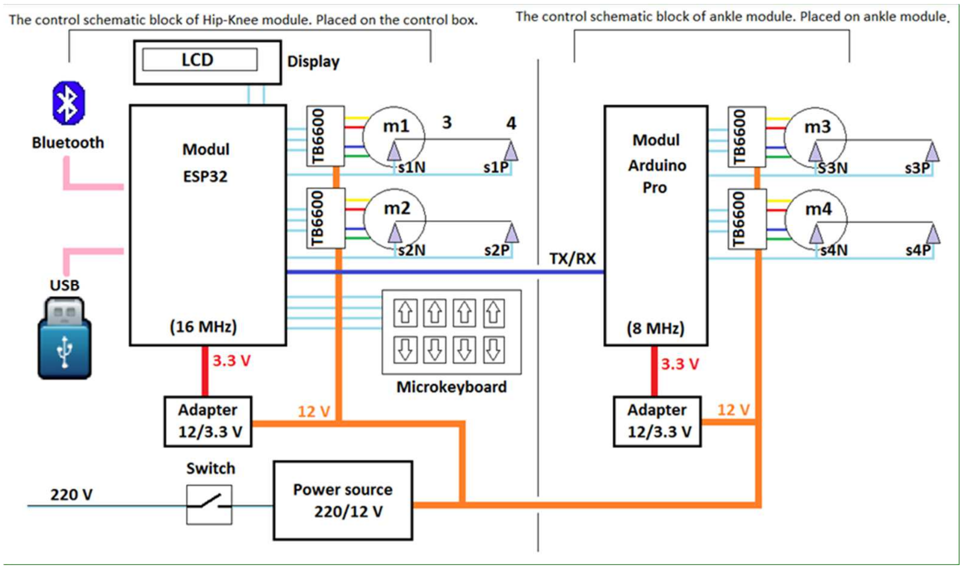


Fig.11. The block diagram of the hardware interface

The use of the feature of authorization/inhibition of motor activity is an aspect not studied so far with adequate attention. When the motors are operated, the stepper motors are powered (one phase). If the motor does not turn, this has a braking effect (braking torque) due to the power consumption that heats the motor. It is important to see whether, without this braking torque, the robot can maintain its working position in conditions where the weight of the parts and the patient can cause unforeseen movements or give up the authorization of rotations, in which case the braking torque disappears and thus the motors heat will be at a lesser level.

4. CONCLUSION

The paper presents the development of RECOVER, a parallel robotic system for rehabilitation. The control system has been developed and a testing interface has been implemented using Visual Basic. A simulation application (within the same user interface) has also been achieved. The robot can be controlled via the GUI (a virtual keyboard) or a 4-buttons micro-keyboard.

The control hardware consists of two microcontrollers that communicate with each other. The first module is the ESP WROOM designed to control the hip-knee motors and the second, the “Arduino Pro Mini-The simple”, that is used to control the motors of the ankle module. In addition, the controller has a Bluetooth receiver / transmitter implemented inside, thus, the control can be taken over from a smartphone with an app specially developed for this wireless communication mode.

The robot structure has a robust construction which, from a mechanical point of view, is capable of performing all the motions for which it was designed, namely hip flexion/extension, knee flexion, ankle flexion/dorsiflexion and flexion/inversion, complying with the required motion amplitudes. Future work will be related to perform the initial tests (with healthy subjects) to assess the robot capabilities and general ergonomics, followed by its validation in medical environment with patients to determine the efficiency of the robot for the rehabilitation of the lower limb.

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DEZVOLTARE INOVATIVĂ A UNUI SISTEM ROBOTIC PARALEL PENTRU REABILITAREA MEMBRULUI INFERIOR

Rezumat: Lucrarea descrie un sistem robotizat având arhitectură paralelă pentru recuperarea medicală a membrelor inferioare, vizând în special pacienții post-AVC cu deficiențe motorii. Lucrarea prezintă modelul experimental al robotului, evidențiind principalele componente ale unei structuri mecanice solide și fiabile, care respectă toate cerințele medicale. Sistemul de control a fost dezvoltat folosind microcontrolere și este prezentată o interfață cu utilizatorul care conţine simularea configurației robotului în timp real.

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