Preliminary results and evaluation of an ankle rehabilitation device

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Abstract. The motivation for designing a new recovery system was based, first of all, on the increased incidence of injuries to the ankle joint. Medical recovery techniques can be applied either by physiotherapists or by robotic systems capable of helping/assisting the physiotherapist, in order to obtain an efficient recovery process. A novel ankle rehabilitation device is being developed, allowing progress monitoring by therapists. The system will allow patients to perform two kinds of exercises (plantar flexion/dorsiflexion and inversion/eversion), hence will own two degrees of freedom. All the required values of the angular amplitudes of the rotational movements are set by the therapist via computer-generated graphical interface. The patients’ exercise is recorded on the host PC for evaluation and progress monitoring. Preliminary results and evaluation of first patient are discussed in this paper. Future medical trials are required to establish the maximum clinical efficacy in rehabilitation.

1. Introduction
There is an increasing of research in medical robotics during the last years [1]-[4]. The ankle joint is a complex consisting of several important structures, which allows both the support of the entire mass of the human body and the execution of movements typical for walking and running. This joint, due to the important role it plays in human activity, is also the most prone to injury. According to a study by Waterman [5], the most common injuries are sprains and have an overall incidence of about 25,000 people/day.

The motivation for designing a new recovery system was based, first of all, on the increased incidence of injuries to the ankle joint. In general, injuries generate a functional disability with major negative implications on locomotor function. Medical recovery is essential, and physical therapy sessions aim to recover the temporarily lost capabilities of the joint. Medical recovery techniques can be applied either by physiotherapists or by robotic systems capable of helping/assisting the physiotherapist, in order to obtain an efficient recovery process [6]. However the large number of patients requesting the help of physiotherapists creates a huge amount of work for them. Therefore, there is a need to develop mechatronic systems that are easy to use, which facilitate the optimal recovery of patients suffering from various ankle diseases. These systems must be easy to program, to perform exercises with various intensities, as well as affordable [7]. By implementing such systems, both the quality of recovery exercises and the quality of time spent in the recovery room will be improved.

Following the analysis of the equipment currently on the market, as well as of the equipment currently researched, it was necessary to develop a robotic system for ankle joint rehabilitation, which
complies with the following requirements: low cost; possibility of programming to change the intensity of the exercises accordingly; the possibility of measuring the force exerted on the leg, so as not to overload the joint.

2. Device design
A novel device for ankle rehabilitation was proposed in previous work that offers two degrees of freedom, necessary for a complete recovery of the joint. Based on the general architecture, mechanism synthesis, kinematic models, 3D CAD models and previous simulations [8]-[17] the ankle rehabilitation device prototype was manufactured, presented in Figure 1.

![Figure 1. Experimental device.](image)

Two servomotors are providing the actuating torque while a PC is used to collect all the data and control the servomotors. One microcontroller is used solely to command the actuators and one is used to collect data and provide visual feedback to the therapist (BasicAtom and SSC32 microcontrollers), Figure 2. The sensory system consists of two digital rotary potentiometers, placed coaxially with the axes of rotation of the driven kinematic element, to measure the angular variations.

![Figure 2. Schematic experimental setup.](image)

A graphic user interface was developed in order to provide visual feedback and allow an easy programming of the rehabilitation exercises (Figure 3). The therapist will set the values corresponding to the rehabilitation exercises, through the computer-generated graphical interface, thus providing the
input values for the microcontroller. It will send the necessary commands to the actuators in order to execute the required movements. The data collected from the position/force transducers will be transmitted for analysis to the controller, resulting in visual feedback for both the patient and the therapist.

Figure 3. Graphic User Interface.

3. Experimental results
Testing of the system was necessary in order to evaluate its performance, in accordance with the recovery requirements. Preliminary tests were performed with no load exercises in order to observe the response of the system. For the flexion/extension and inversion/eversion movements the amplitudes used for exercises were 25 degrees flexion, 45 degrees extension, 45 degrees inversion (right foot) and 25 degrees eversion (right foot).

Figure 4 shows the amplitude of the movements monitored during the test. With red color one can notice the theoretical trajectory, generated with the help of mathematical models while in blue is represented the trajectory of the signal collected from the rotary potentiometers, function on the input angle. Values above 0 (Figure 4.a) correspond to flexion, while values on the negative axis correspond to extension. For the inversion/eversion movement (Figure 4.b) the positive values of the angle represent the eversion while the negative values represent the inversion, for a right leg. A linear trajectory can be observed, close to the calculated values, for both movements to be recovered.

One patient volunteered to test the rehabilitation platform after suffering from a navicular fracture of the right foot. After the required time of rest in cast (30 days), the recovery process was imperious, since the patient was in pain when walking and had a swollen foot. The therapist recommended several exercises for flexion/extension and inversion/eversion.

The experimental protocol for testing the subject consisted of the following stages:
- first the mechatronic system and the principle of operation was described to the patient;
- safety was guaranteed throughout the use of the device;
- it was explained to the subject that he can interrupt the test at any time;
- The next step was to position the subject on the rehabilitation system - the starting position of the therapy was with the knee in flexion, in order to obtain a 90° angle between the thigh and leg, and the sole of the foot perfectly placed on the driven element of the system. This proper alignment of
the subject was important for the precision of the results.
- the tests with the rehabilitation system consisted in performing flexion/extension and inversion/eversion exercises in order to track their angular amplitudes and to monitor the patient's evolution in time.

![Figure 4](image1.png)

**Figure 4.** Test results, angular displacements: (a) flexion/extension movement; (b) inversion/eversion movement.

After the patient acknowledged the recovery protocol and agreed to start therapy with the robotic system, his functional abilities were noted. The patient, placed on the chair, with his right foot on the device, started the first recovery exercises with amplitudes of $+20$:-$25$ degrees for flexion/extension and $+15$:-$20$ degrees for inversion/inversion (Figure 5). Results obtained from the position transducers regarding the amplitude of movement of the ankle joint were recorded, for each set of exercises, to follow the evolution over time of the patient. Deviations from the proposed trajectory can be observed due to the increased rigidity of the joint. Each exercise was repeated at least 20 times a day.

![Figure 5](image2.png)

**Figure 5.** Patient’s first day of rehabilitation exercises, angular displacements: (a) flexion/extension movement; (b) inversion/eversion movement.

After 30 days of continuously rising the amplitude of the exercises, the last ones performed by the patient have angular amplitudes of $+25$:-$40$ degrees for flexion / extension and $+25$:-$35$ for
eversion/inversion. The progress made by the patient is obvious especially in the case of the eversion movement, where the stiffness was very high (Figure 6).

![Figure 6](image)

**Figure 6.** Patient’s last day of rehabilitation exercises, angular displacements: (a) flexion/extension movement; (b) inversion/eversion movement.

Figure 7 shows the patient's evolution regarding the angular amplitude performed by the ankle joint. The evolution highlights the final degree of recovery of the patient compared to the initial day. As showed, the patient initially has a limited range of motion of 20 degrees for flexion, 25 extension, 15 for eversion and 20 degrees for inversion. A remarkable improvement is observed after the completion of recovery therapy.

![Figure 7](image)

**Figure 7.** Comparative results of rehabilitation exercises, angular displacements: (a) flexion/extension movement; (b) inversion/eversion movement.

4. Conclusions
The evolution of the patient range of motion shows an noticeable improvement: with 5 degrees for flexion, 15 degrees for extension, 10 degrees for inversion and 15 degrees for eversion movement. Also, at the beginning of the rehabilitation the predefined trajectory was hard to follow, because of ankle joint stiffness, resulting in deviation from the projected trajectory, but with the increase of mobility the exercises become easier to accomplish.
The two DOF robotic device presented in this paper could provide easy rehabilitation and visual feedback for people suffering from ankle related injuries. More clinical tests are required in order to extend the use of the device to therapist offices and homes.

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