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DEVELOPMENT OF A ROBOTIC PLATFORM FOR ANKLE JOINT REHABILITATION

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Abstract: *The ankle structure holds one of the most important role in the human biomechanics. Due to complexity of everyday activities this joint is the most prone to be injured part of the lower limb. This fact motivated the designing of a rehabilitation robotic system, which could be able of helping/assisting the physiotherapist, in order to obtain an efficient recovery process. A novel ankle rehabilitation device was developed, allowing progress monitoring by therapists. Some structural, kinematic and designing aspects regarding this rehabilitation system are discussed in this paper. Also, preliminary experimental results and evaluation of first patient are presented. Future trials are required to establish the maximum clinical efficiency of this platform in ankle joint rehabilitation.*

Key words: *ankle joint, rehabilitation, robotic system.*

1. INTRODUCTION

During the last decades, the interest in research focused on assistive technologies for rehabilitation is growing, due to the growing number of aging population that requires assistance after injuries [1]. The ankle has an important role in everyday life of people. This conducts to often injuries, as fracture, strain or sprain, with a high incidence of the last one [2], which need rehabilitation.

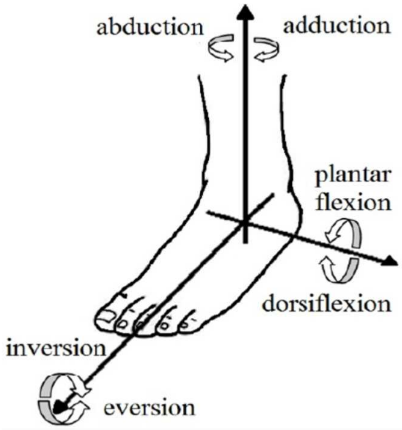

Fig. 1. Ankle joint movements.

Usual rehabilitation therapies use simple devices and require the assistance of a therapist. The exercises are low-term, repetitive and they require patients and therapists effort. Also, the patient is not accessible. To counteract these drawbacks many robot-assisted ankle rehabilitation devices have been proposed till now [3-4].

To achieve a fully recovered ankle joint one must consider ankle movements and range of motion: from 0 to 25 degrees for flexion (dorsiflexion) and eversion, and 0 to 50 degrees for plantar flexion (extension) and inversion, for a healthy subject (Figure 1), [5].

In this paper, a light weight, low cost and easy to manufacture ankle rehabilitation devices is discussed.

2. STRUCTURAL SYNTHESIS

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As starting point of designing the ankle rehabilitation device we have the ankle related movements. The ankle joint can generate three rotations, but only two rotations are most common used for ankle rehabilitation: dorsiflexion/plantar flexion and inversion/eversion. Therefore the system should be spatial oriented, allowing rotations around two perpendicular axes, hence a spatial two degrees of freedom (DOF) mechanism is needed. It means that the driven link of the mechanism (the plate supporting the foot) should have 2 DOF (Figure 2), [6].

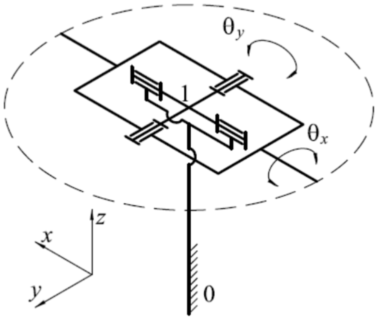


Fig. 2. 2 DOF moving platform [6].

To drive this link, many mechanism structures could be used but, for the rehabilitation device discussed in this paper, we proposed a 2-RSU/U mechanism (Figure 3).

The entire mechanism of the robotic rehabilitation platform based on a 2-RSU/U structure is shown in Figure 4, [7-11].

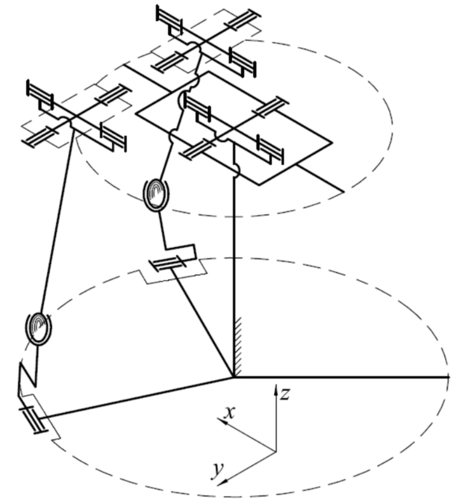


Fig. 3. 2-RSU/U mechanism.

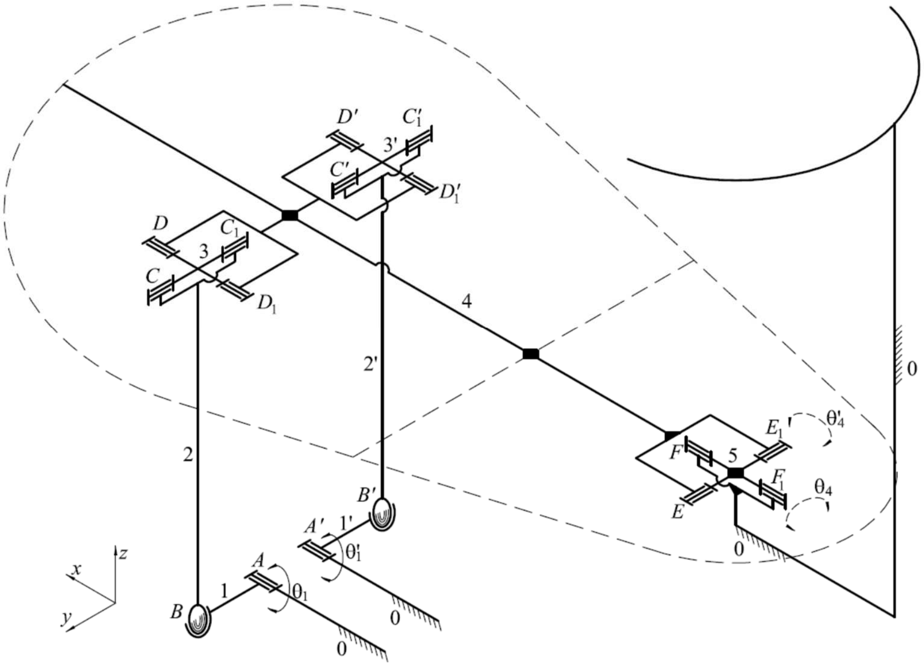


Fig. 4. Kinematics of the mechanism proposed for the rehabilitation robotic device [10].

3. KINEMATICS

The robotic mechanism has a fixed frame (link 0), connected to the ground and also to the shank. For recovering the two mentioned ankle movements, the foot will be placed on the platform (link) 4. The amplitudes of these movements are variable and controlled progressively, in order to avoid ankle injuries.

The platform has the links 1 and 1' as actuated links and the last link, 4, is a driven one. This last link will support the sole, which has to be fixed (through some belts) on it. If the links 1 and 1' are rotating with the same angle, $\theta_1 = \theta'_1$, (both in clockwise or counterclockwise direction), the link 4 will be driven with θ_4 angle, around *x* axis, producing inversion - eversion movement of the ankle joint. If these links are rotating with the same angle but in opposite direction, $\theta_1 = -\theta'_1$, the link 4 will be driven with θ'_4 angle, around *y* axis, producing plantar flexion - dorsiflexion movement.

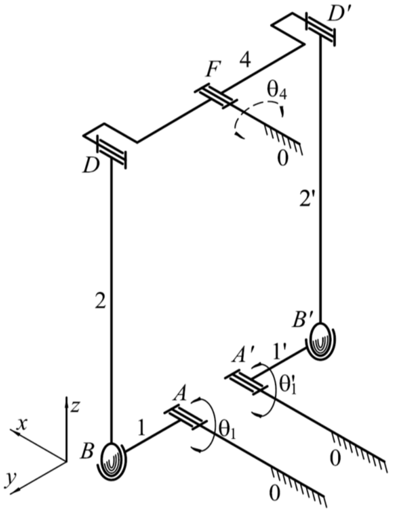


Fig. 5. Equivalent mechanism for inversion – eversion movement with two actuated links.

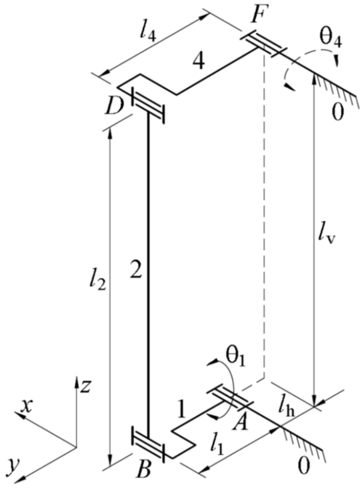


Fig. 6. Simplified equivalent mechanism for inversion – eversion movement, with one actuated link [10].

Let us consider the first case mentioned above (when $\theta_1 = \theta'_1$). The equivalent mechanism for this movement is shown in Figure 5. Even if this mechanism has two actuated links, it could work using a single motor (with *A*, *B*, *D* and *F* joints). Because it is a planar linkage, the spherical joint *B* could be replaced by a rotational one (Figure 6).

Direct kinematics leads to

$$\theta_4 = 2\mathrm{atan}\left(\frac{-\mathrm{B}_1 \pm \sqrt{A_1^2 + B_1^2 - C_1^2}}{C_1 - A_1}\right), \qquad (1)$$

where:

$$\begin{cases} A_1 = -2l_4\left(l_h + l_1\cos\theta_1\right) \\ B_1 = 2l_4\left(l_v - l_1\sin\theta_1\right) \\ C_1 = 2l_1\left(l_h\cos\theta_1 - l_v\sin\theta_1\right) + l_1^2 - l_2^2 + l_4^2 + l_v^2 + l_h^2 \end{cases} .(2)$$

Solving inverse kinematics problem, we get:

$$\theta_1 = 2\mathrm{atan}\left(\frac{-\mathrm{B}_2 \pm \sqrt{A_2^2 + B_2^2 - C_2^2}}{C_2 - A_2}\right), \qquad (3)$$

where:

$$\begin{cases} A_2 = 2l_1\left(l_h - l_4\cos\theta_4\right) \\ B_2 = -2l_1\left(l_v + l_4\sin\theta_4\right) \\ C_2 = 2l_4\left(l_v\sin\theta_4 - l_h\cos\theta_4\right) + l_1^2 - l_2^2 + l_4^2 + l_v^2 + l_h^2 \end{cases} .(4)$$

We are considering now the mechanism responsible for the plantar flexion-dorsiflexion movement, $\theta_1 = -\theta'_1$ (Figure 7). To solve the kinematics problem an equivalent mechanism is used, in which the spherical joint *B* will be replaced with a universal kinematic joint. Again, this mechanism could work using a single actuator (Figure 8).

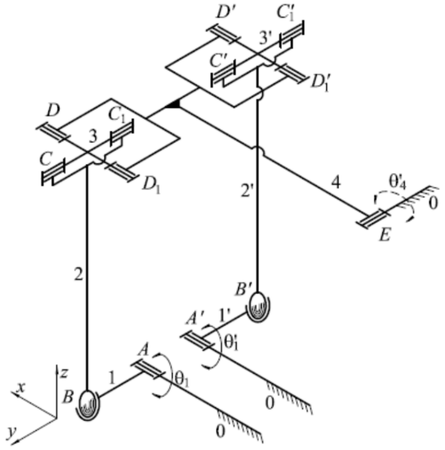


Fig. 7. Equivalent mechanism for flexion – extension movement with two actuated links.

Solving the kinematics problem, we will get:

$$\theta'_4 = 2\operatorname{atan}\left(\frac{-\mathrm{B}_3 \pm \sqrt{A_3^2 + B_3^2 - C_3^2}}{C_3 - A_3} \right), \qquad (5)$$

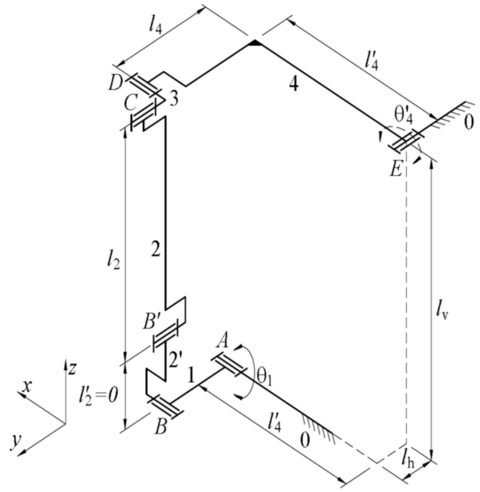


Fig. 8. Simplified equivalent mechanism for flexion – extension movement, with one actuated link [10].

where

$$\begin{cases} A_3 = -2l'^2_4 \\ B_3 = -2l'_4\, l_2 + 2l_4 l'_2 \sin\theta_1 \\ C_3 = l_1^2 - l_2^2 + l_4^2 + l_v^2 + l_h^2 + 2l'^2_4 - 2l_2 l_4 - \\ \quad - 2l_1 l_v \sin\theta_1 + 2l_1(l_h - l_4)\cos\theta_1 \end{cases}, \qquad (6)$$

and

$$\theta_1 = 2\operatorname{atan}\left(\frac{-\mathrm{B}_4 \pm \sqrt{A_4^2 + B_4^2 - C_4^2}}{C_4 - A_4} \right), \qquad (7)$$

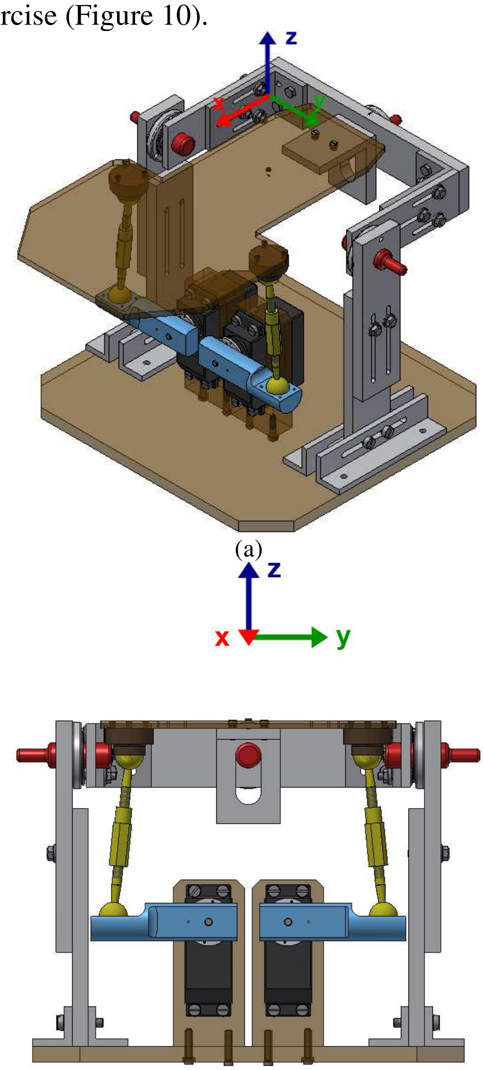
where:

$$\begin{cases} A_4 = 2l_1(l_h - l_4) \\ B_4 = 2l_1(l'_4 \sin\theta'_4 - l_v) \\ C_4 = l_1^2 - l_2^2 + l_4^2 + l_v^2 + l_h^2 + 2l'^2_4 - 2l_h l_4 - \\ -2l'_4(l_2 \sin\theta'_4 + l'_4 \cos\theta'_4) \end{cases}. \qquad (8)$$

4. CAD MODEL AND SIMULATION

Based on mechanism synthesis and kinematic models, a 3D CAD model has been designed (see Figure 9).

In order to demonstrate that the platform offers to the driven link the angular strokes necessary for a complete recovery for the ankle joint, for the two flexion-extension and inversion-eversion movements, a simulation of the 3D virtual model was simulated. The values required for the geometric synthesis were chosen on the basis of anatomical considerations and overall dimensions as follows: $l_h = 25$ [mm], $l_4 = 75$ [mm] and $l_v = 101.5$ [mm]. Then, $l_1 = 60$ [mm] and $l_2 = 103$ [mm] are resulting from the dimension synthesis (approximated to integer values). Attached to the CAD model was an axis system originating at a point placed at 70 [mm] above the sole support plate 4 (in the center of the ankle joint), in order to record the values corresponding to the rehabilitation exercise (Figure 10).



(a)

(b)

Fig. 9. CAD design of the rehabilitation device: a) 3D view; b) front view [11].

The position angle value of the driven link, θ'_4, will vary between -25° and 0° for flexion movement and between 0° and 50° for extension movement, resulting in a variation of the position angle values of the driving links as follows: $\theta_1 = -32.4^o \div 59^o$ and $\theta'_1 = -59^o \div 32.4^o$ (Figure 11).

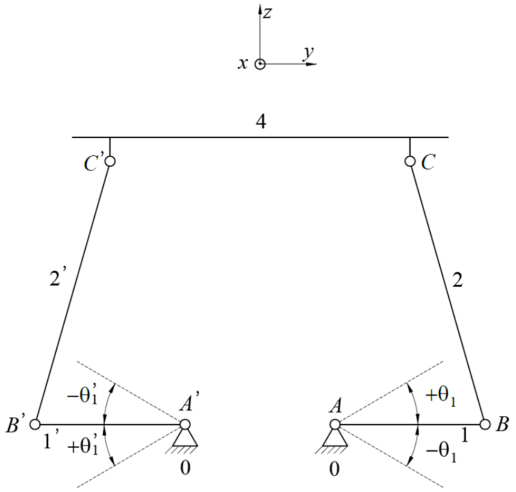


Fig. 10. Reference axis system for simulation.

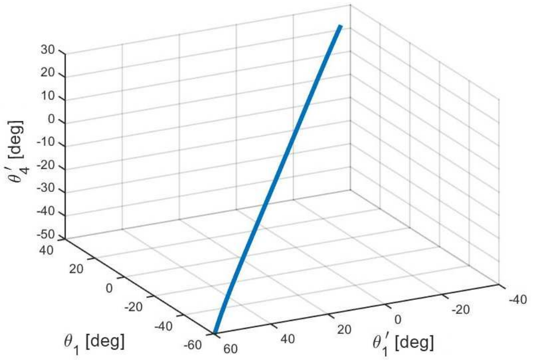


Fig. 11. Angular position of the driven link related to the angular positions of the driving links for pure flexion-extension movement.

The surface shown in Figure 12 represents the variation of the driven link angular position θ'_4 related to the limit values of the driving links angular positions θ_1 and θ'_1, limit values that ensure the two rehabilitated movements of the ankle joint.

For the inversion-eversion movement, the value of the position angle of the driven link will have a variation between -50º and 50º. For a healthy person, this angle should vary between 0º and 50º for inversion movement and between -25º and 0º for eversion movement, for the right leg.

These values are reversed for the left leg as follows: between 0º and 25º for eversion movement and between -50º and 0º for inversion movement. In order to obtain the mentioned values of the position angle of the driven link, the values of the position angles of the driving links vary in the range $\theta_1 = \theta'_1 = -73.8^o \div 73.8^o$ (Figure 13).

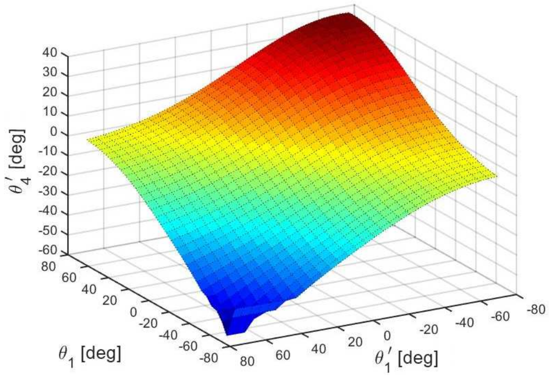


Fig. 12. Angular position θ'_4 of the driven link related to the angular positions of the driving links for both flexion-extension and inversion-eversion movements.

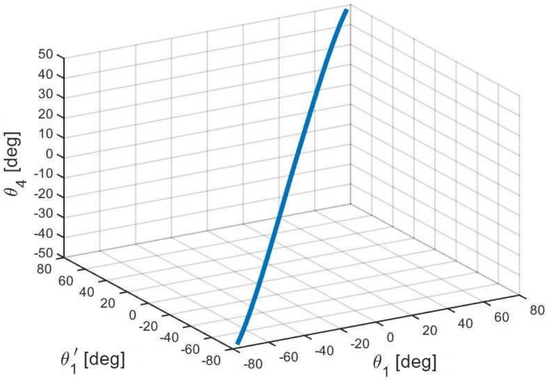


Fig. 13. Angular position of the driven link related to the angular positions of the driving links for pure inversion-eversion movement.

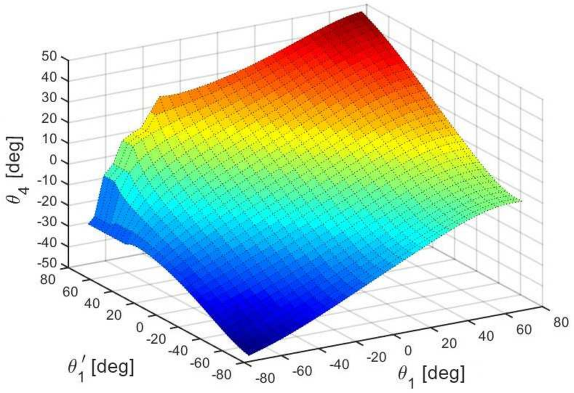


Fig. 14. Angular position θ_4 of the driven link related to the angular positions of the driving links for both flexion-extension and inversion-eversion movements.

The surface shown in Figure 14 represents the variation of the driven link angular position θ_4 related to the limit values of the driving links angular positions θ_1 and θ'_1, limit values that ensure the two rehabilitated movements of the ankle joint.

5. EXPERIMENTAL PROTOTIPE

The general architecture of a rehabilitation system is shown in Figure 15. The therapist should set the values of the rehabilitation exercise amplitudes through the graphical interface generated by the computer, providing the input values for the microcontroller. This microcontroller will send the range of the necessary angular strokes executed by the actuators. The data collected from the position/force sensors will be sent back, resulting in visual feedback for both the patient and the therapist.

Based on the general architecture and 3D design shown before, a first experimental devise has been manufactured (Figure 16). Two servomotors are actuating the driving links, which will result in the movement of the support link (driven link, the plate which support the sole). The actual angular positions of this plate are measured using two rotational resistive sensors. Two microcontrollers are used to control the device, one is recording the angular position values from the sensors, and the other one sends information to the motors. Future work is required to be done for safety measures. For safety reasons (to avoid injuries or supplementary pain to the patient), torque sensors will be used for each ankle movement. In this manner, the robotic platform should rotate the driven link to the position limited by the maximum torque imposed by the user and it should offer a gradual recovering of the ankle joint.

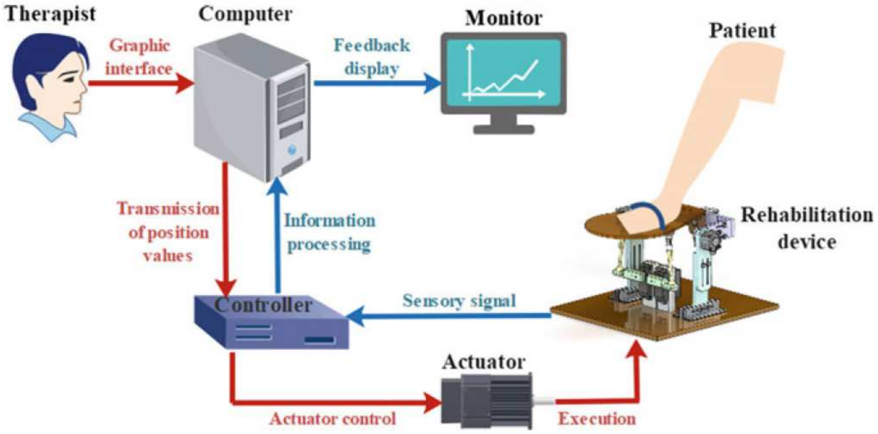


Fig. 15. General architecture of the rehabilitation system [10].

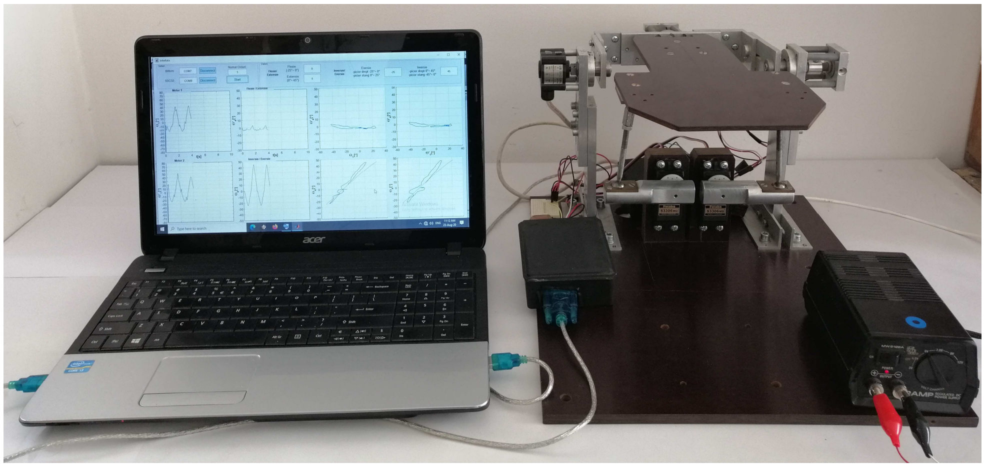
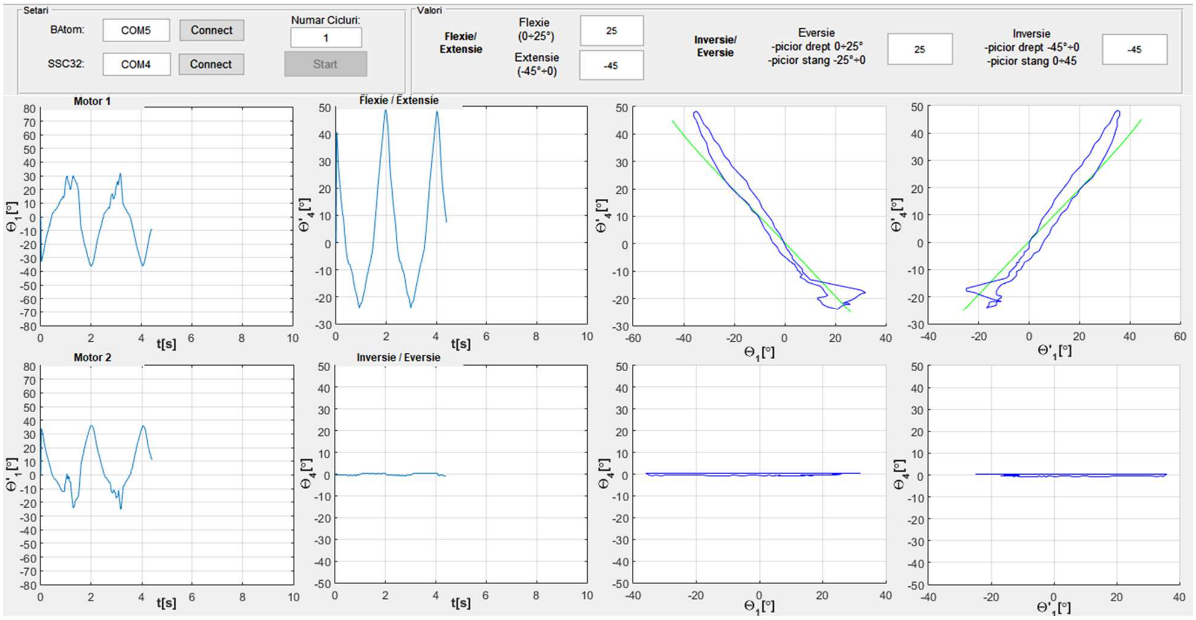


Fig. 16. Experimental prototipe of the rehabilitation system.

A graphic user interface was developed in order to provide visual feedback and to allow an easy programming of the rehabilitation exercises (Figure 17). 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.


Setari

BAtom: COM5

SSC32: COM4

Numar Cicluri: 1

Valori

Flexie/ Extensie

Flexie (0÷25°): 25

Extensie (-45°÷0): -45

Inversie/ Eversie

Eversie -picior drept 0÷25° -picior stang -25°÷0: 25

Inversie -picior drept -45°÷0 -picior stang 0÷45: -45

Fig. 17. Graphic User Interface [12].

6. EXPERIMENTAL RESULTS

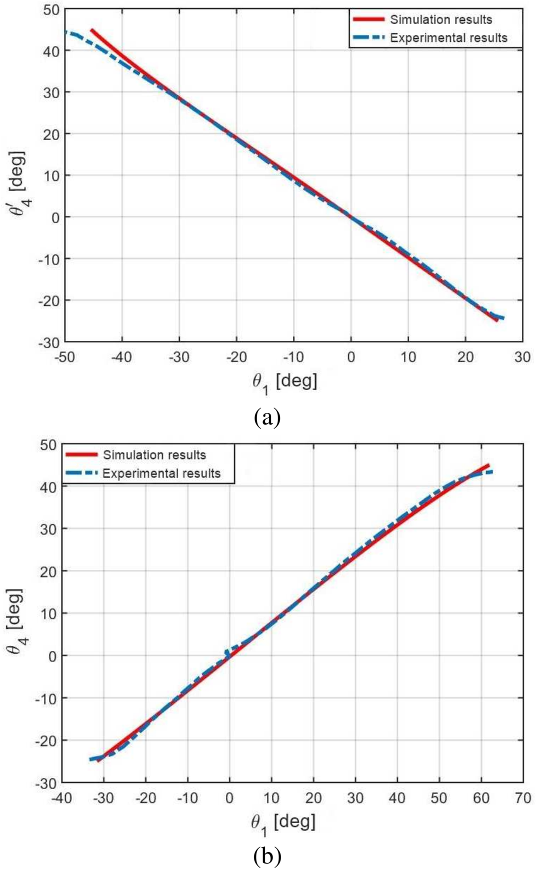
After treating the condition from a medical point of view (surgical or non-surgical), the physician recommends to the patient to start some physical therapy sessions, in order to obtain a complete recovery of the joint. In this sense, a meeting is established between the patient – physician – physiotherapist, with the role of elaborating the recovery criterion (passive or active) that must be applied to the patient. The medical recovery program is based on medical diagnosis. Consequently, the physician outlines to the physiotherapist the strengths that he must follow during the medical recovery and he/she recommends caution, especially if the patient has had a previous medical history in the ankle joint area (treated or partially treated), [12].

Because the therapy is performed with the help of the robotic system, in this case the role of the physiotherapist is only to assist the therapy. At the same time, he must describe to the patient the robotic system that will recover him/her (to remove the patient's reluctance to his presence) and explain the benefits that the system can offer to medical recovery.

Testing of the rehabilitation system was necessary to evaluate its performance, in accordance with the imposed recovery requirements. It was wanted to monitor the amplitude of movement, without loading the robotic system, for maximum rehabilitation values. Complete displacement races were performed for the flexion-extension and inversion-eversion movements, namely: amplitudes of 25 degrees for flexion, 45 degrees for extension, 45 degrees for inversion (right foot) and 25 degrees for eversion (right foot).

Figure 18 shows the amplitude of the movements monitored during testing. One can notice, in red (continue line), the theoretical trajectory, generated with the help of mathematical models, while in blue (dashed line) is represented the trajectory of the experimental data recorded from the angular position sensor. The positive angular position values (Figure 18.a) correspond to the extension, while the values on the negative axis correspond to the flexion. For the inversion-eversion movement (Figure 18.b), the positive values of the angular position correspond to the inversion, while the negative values correspond to the eversion, for the right leg. A linear trajectory can be observed and close to the calculated values, for both movements to be recovered.

It was desired to apply a medical recovery therapy on patients with deficiencies in the ankle joint. In this sense, a patient volunteered to test the robotic system, after suffering a fracture of the navicular bone in his right leg (Figure 19). The rest period in the plaster cast was 30 days, after which it was recommended to start the recovery sessions.



(a)

(b)

Fig. 18. Angular amplitudes obtained during the tests of the robotic system: a) for flexion-extension movement; b) for inversion-eversion movement.

Due to the long immobilization, the patient suffered from peripheral endemism to the affected leg, difficulty walking and performing daily activities, due to the increased rigidity of the ankle joint. The physiotherapist recommended several types of exercises for flexion-extension and inversion-eversion movements, with a frequency at least once a day.

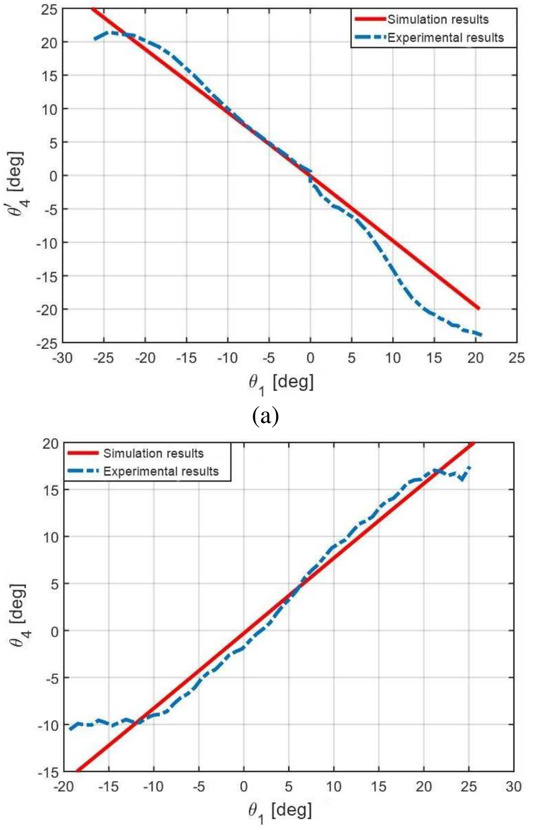
Fig. 19. Navicular bone fracture of the volunteer patient.

Before starting the therapy, the anthropometric characteristics of the healthy subject under test were noted in a database, as well as some general information about it, related to: age, sex, profession, medical history, etc.

After the patient was explained the recovery protocol and he agreed to start therapy with the robotic system, its functional capabilities were noted from the start of therapy. Starting from the angular amplitudes observable with the naked eye, tests were performed on the robotic system by progressively increasing them, obtaining exactly the range of permissible values for rehabilitation exercises.

The patient, seating on a chair, with his right foot placed on the support plate of the rehabilitation system, began the first recovery exercises with amplitudes of $\theta'_4 = -20^{\mathrm{o}} \div 25^{\mathrm{o}}$ for flexion-extension movement and $\theta_4 = -15^{\mathrm{o}} \div 20^{\mathrm{o}}$ for eversion-inversion movement (Figure 21). The results obtained from the angular position transducers regarding the movement angular amplitude of the ankle joint were recorded, for each set of exercises, in order to follow the evolution in 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.

Checking the angular amplitudes of the ankle joint was performed before each session, in order to increase the intensity of the exercises. In the middle of the recommended recovery period, of 3 weeks (ie after 10 days), it was possible to observe the improvement of these values, so that the angle θ'_4 corresponding to the flexion-extension movement varies between -22 and +30 degrees, and the angle θ_4 corresponding to eversion-inversion movement varies between -23 and +30 degrees. This time, the deviations from the proposed trajectory are much smaller.



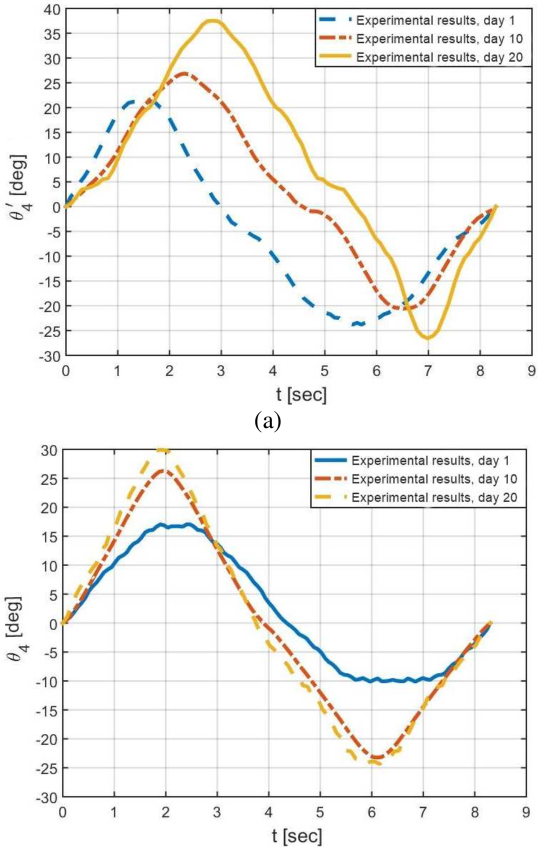
(a)

(b)

Fig. 20. Results of rehabilitation exercises, day 1: a) flexion-extension; b) inversion-eversion.

The last exercises performed by the patient have angular amplitudes of -25 ... + 40 degrees for flexion-extension movement and -25 ... + 35 for eversion-inversion movement. The progress made by the patient is obvious, especially in the case of the inversion movement, where the stiffness was very high.

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



(a)

(b)

Fig. 21. Results of rehabilitation exercises, in time: a) flexion-extension; b) inversion-eversion.

7. CONCLUSION

In this paper, some structural, kinematic and designing aspects regarding a robotic system for ankle joint rehabilitation have been discussed. Also, preliminary experimental results and evaluation of a first patient have been presented. The evolution of the patient range of motion shows an noticeable improvement. Also, at the beginning of the rehabilitation process 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 became easier to accomplish. The robotic system discussed here 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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Dezvoltarea unei platforme robotice pentru reabilitarea articulației gleznei

Rezumat: Structura gleznei deține unul dintre cele mai importante roluri în biomecanica umană. Datorită complexității activităților de zi cu zi, această articulație este cea mai predispusă a fi rănită a membrului inferior. Acest fapt a motivat proiectarea unui sistem robot de reabilitare, care ar putea ajuta / asista kinetoterapeutul, pentru a obține un proces eficient de recuperare. A fost dezvoltat un nou dispozitiv de reabilitare a gleznei, care permite monitorizarea progresului de către terapeuți. Unele aspecte structurale, cinematice și de proiectare referitoare la acest sistem de reabilitare sunt discutate în această lucrare. De asemenea, sunt prezentate rezultatele experimentale preliminare și evaluarea primului pacient. Sunt necesare studii viitoare pentru a stabili eficiența clinică maximă a acestei platforme.

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