

# Design, modelling and simulation aspects of an ankle rehabilitation device

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**Abstract.** Ankle injuries are amongst the most common injuries of the lower limb. Besides initial treatment, rehabilitation of the patients plays a crucial role for future activities and proper functionality of the foot. Traditionally, ankle injuries are rehabilitated via physiotherapy, using simple equipment like elastic bands and rollers, requiring intensive efforts of therapists and patients. Thus, the need of robotic devices emerges. In this paper, the design concept and some modelling and simulation aspects of a novel ankle rehabilitation device are presented.

## 1. Introduction

There is an increase demand for assistive technologies in the last few years, as statistics show a growing number of aging population, that require assistance, while the number of people that can provide it is relatively low [1]. Rehabilitation robotics is a special branch of robotics focused on devices, which can provide direct and physical help and support to patients, after a severe physical trauma. The main specifications for these devices are concerning safety, comfort, precision of assistive force, size and weight.

Ankle injuries are very common in sports and daily life, due to the importance of this articulation in keeping the balance of an individual, and also to support the body weight in normal activities [2]. Traditionally, ankle injuries are rehabilitated via physiotherapy, which requires intensive efforts of therapists and patients over long sessions. Also, without sufficient rehabilitation approximately 38% of people will have recurrent activity limitation, affecting their everyday life [3]. For the rehabilitation of the ankle joint we find a number of simple devices, used for specific exercises, such as elastic band, wooden wobble board or foam rollers. We can conclude that ankle exercises are long-term and repetitive and cannot offer information about patient evolution. Thus, the need for easy-to-use mechatronic devices emerges. These systems must be easily programmed, financially affordable and they also need to offer the two movements (flexion-extension and inversion-eversion) required for a complete recovery of the injured ankle.

Various types of robotic devices have been developed in the last years for lower limb rehabilitation [4, 5, 6]. We can divide these devices in the following general categories: exoskeleton, orthoses and end-effectors robots. We further present a few examples for each category. Treadmill based exoskeletons offer a body weight support system and a lower limb exoskeleton for patients to wear. For example, the Lokomat is a typical treadmill based exoskeleton where the patient legs are strapped



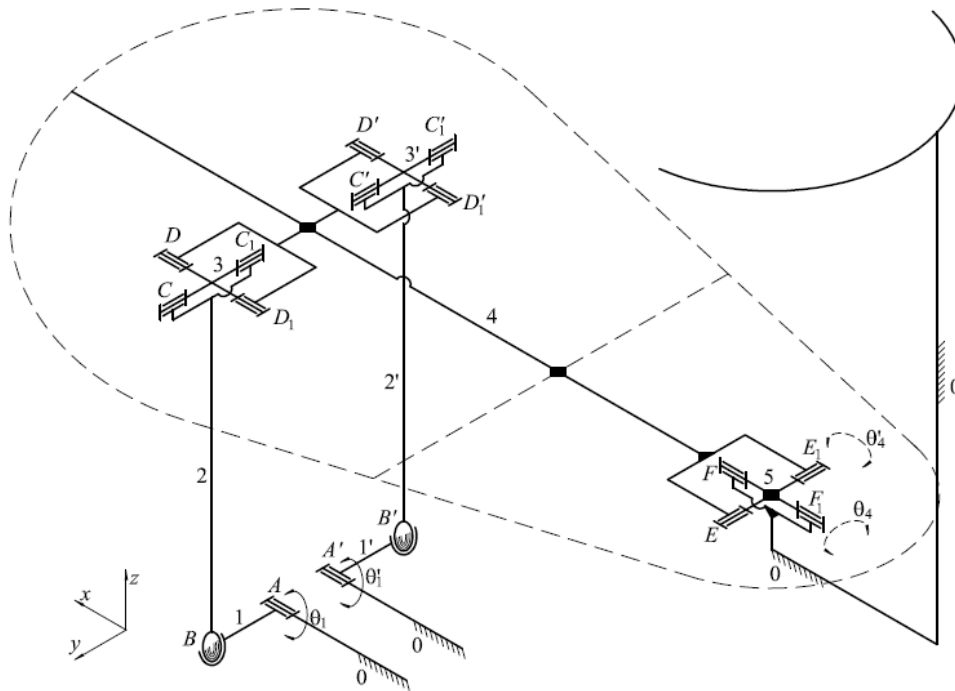
into an adjustable frame, to provide powered assistance at the hip and knee [7]. LOPES is a new gait training robot that combines a translatable pelvis segment with a leg exoskeleton. It has three actuated joint, for hip, knee and ankle [8]. At the University of Delaware has been developed ALEX, a powered leg orthosis with linear actuators at the hip and knee joint, to provide assistance to the patient during walking [9]. Another approach to ankle rehabilitation is represented by ankle-foot orthosis. Lower Limb Exerciser with Intelligent Alloys (Leia) [10] has a pair of solid state motors based on shape memory alloy NiTi, providing a  $40^\circ$  motion around the ankle joint axis, when it is powered by a direct electric current. Patar, et. al. [11] developed an easy to wear, and low cost orthosis. Their design has one degree of freedom, allowing dorsiflexion –plantarflexion movement, using a DC servomotor. It can be used also to provide support for the foot's natural position. Anklebot [12], designed by engineers at MIT Newman Laboratory for Biomechanics and Human Rehabilitation, is a robot mounted on a brace, attached to a custom shoe. This robot can move the foot in different directions, following a preset program. It has electrodes that measure the stiffness of a joint and progress over time. In the case of platform based end-effector devices the patient feet is fixed on the platform, which is controlled by programmable systems. A parallel robot was designed by Yoon, et al. [13] and it is a reconfigurable robot, which has a large range of various exercises. This robot has four degrees of freedom (d.o.f.) and it consists of two platforms and three feet, driven by four pneumatic actuators. Another soft parallel ankle rehabilitation robot was designed by P. K. Jamwal et al. [14] that provides three rotational d.o.f., using two parallel platforms: a fixed one, U shaped, having a structure for leg support, and a mobile one. The mobile platform is driven by four air artificial muscles, which are mounted on the leg support, connected to the platform through cables. An older Stewart platform, named "Rutgers Ankle" [15] is connected to a computer with running reality-based exercises. It has six d.o.f. and double-acting pneumatic cylinders as actuators. This platform is the most used for ankle rehabilitation, due to its complexity of exercises. Robot-assisted lower limb rehabilitations presets many advantages in concerns of effectiveness and repeatability. Nevertheless, the solutions existing on the market are still not convenient, in terms of cost, dimensions or complexity.

## 2. Design and mathematical modelling of the proposed device

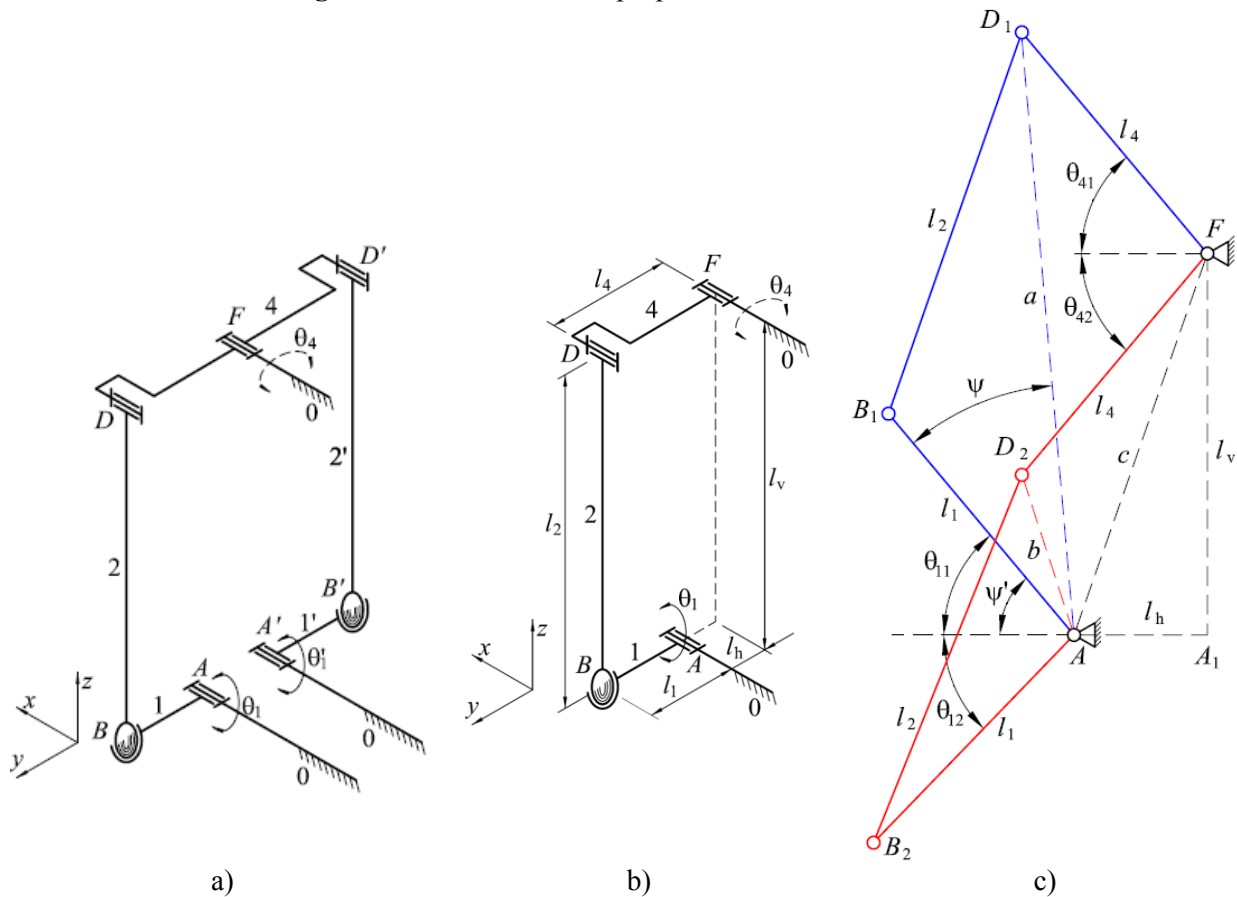
Our goal is to find light weight, low cost and easy to manufacture solutions for ankle rehabilitation platforms [16-19]. Also, in designing the device we must consider the ankle related movements. This joint can generate three rotations, but only two rotations are required for ankle rehabilitation: dorsiflexion/plantar flexion and inversion/eversion. Thus the system should be a spatial mechanism, allowing rotations around two perpendicular axes (hence, two degrees of freedom).

Considering all the above requirements, we propose a device based on simple spatial four bar mechanism (kinematics presented in Figure 1). This device has a fixed frame (link 0) connected to the ground and also to the shank. The foot will rest on the plate 4, the bars 1 and 1' are actuated links and the plate 4 is the driven link. This last link will support the sole, which has to be fixed on it. If the links 1 and 1' are rotating with the same angle,  $\theta_1 = \theta'_1$ , the link 4 will be driven with  $\theta_4$  angle around  $x$  axis, producing inversion/eversion movement of the ankle joint. Rotating 1 and 1' links in opposite direction, but with same angle,  $\theta_1 = -\theta'_1$ , link 4 will produce plantar flexion/dorsiflexion movement around  $y$  axis, with an amplitude given by  $\theta'_4$  angle.

For a simple geometrical synthesis, we use a simplified planar mechanism for the inversion-eversion movement (Figure 2c). We assume that for  $l_h$ ,  $l_v$  and  $l_4$  are known (due to anatomical and space considerations). Also, we impose the  $\theta_4$  angle ( $\theta_{41}$  and  $\theta_{42}$  for inversion, eversion respectively) and  $\theta_1$  (composed from  $\theta_{11}$  and  $\theta_{12}$ ) that represents the angle between the extreme positions of the crank and the horizontal plane. Solving the problem, we will find the unknown link lengths,  $l_1$  and  $l_2$  respectively:



**Figure 1** Kinematics of the proposed rehabilitation device



**Figure 2.** Mechanism for inversion/eversion movement: a) entire spatial mechanism with two d.o.f.; b) half spatial mechanism with one d.o.f.; c) equivalent planar mechanism with one d.o.f.

$$l_1 = \frac{a^2 - b^2}{-2b \cos(\psi' + \theta_{12}) + 2a \cos \psi} \quad (1)$$

$$l_2 = \sqrt{l_1^2 + b^2 - 2l_1 b \cos(\psi' + \theta_{12})} \quad (2)$$

where:

$$a = \sqrt{l_v^2 + l_h^2 + l_4^2 - 2(l_v^2 + l_h^2)^{1/2} l_4 \cos(\psi'' + \theta_{41} + \theta_{42})} \quad (3)$$

$$b = \sqrt{l_v^2 + l_h^2 + l_4^2 - 2(l_v^2 + l_h^2)^{1/2} l_4 \cos \psi''} \quad (4)$$

$$\psi' = \frac{\pi}{2} + \arccos\left(\frac{l_v}{\sqrt{l_h^2 + l_v^2}}\right) - \arccos\left(\frac{l_h^2 + l_v^2 + b^2 - l_4^2}{2b\sqrt{l_h^2 + l_v^2}}\right) \quad (5)$$

$$\psi = \frac{\pi}{2} + \arccos\left(\frac{l_v}{\sqrt{l_h^2 + l_v^2}}\right) - \arccos\left(\frac{l_h^2 + l_v^2 + a^2 - l_4^2}{2a\sqrt{l_h^2 + l_v^2}}\right) - \theta_{11} \quad (6)$$

$$\psi'' = \frac{\pi}{2} - \arccos\left(\frac{l_v}{\sqrt{l_h^2 + l_v^2}}\right) - \theta_{42} \quad (7)$$

Similarly, for a geometrical synthesis of the mechanism for the flexion/extension movement we use Figure 3c. In this case, we assume that  $d_1, e_1, d_2, e_2$  and  $l_v$  are known from the geometrical synthesis of the inversion/eversion mechanism, with:  $d_1 = l_1 \sin \theta_{11}$ ,  $e_1 = l_2 \sin \theta_{21}$ ,  $d_2 = l_1 \sin \theta_{12}$ ,  $e_2 = l_2 \sin \theta_{22}$ . If we will impose the maximum angles for flexion movement,  $\theta'_{41}$ , and extension respectively,  $\theta'_{42}$ , we will get  $l'_4$  for these extreme positions:

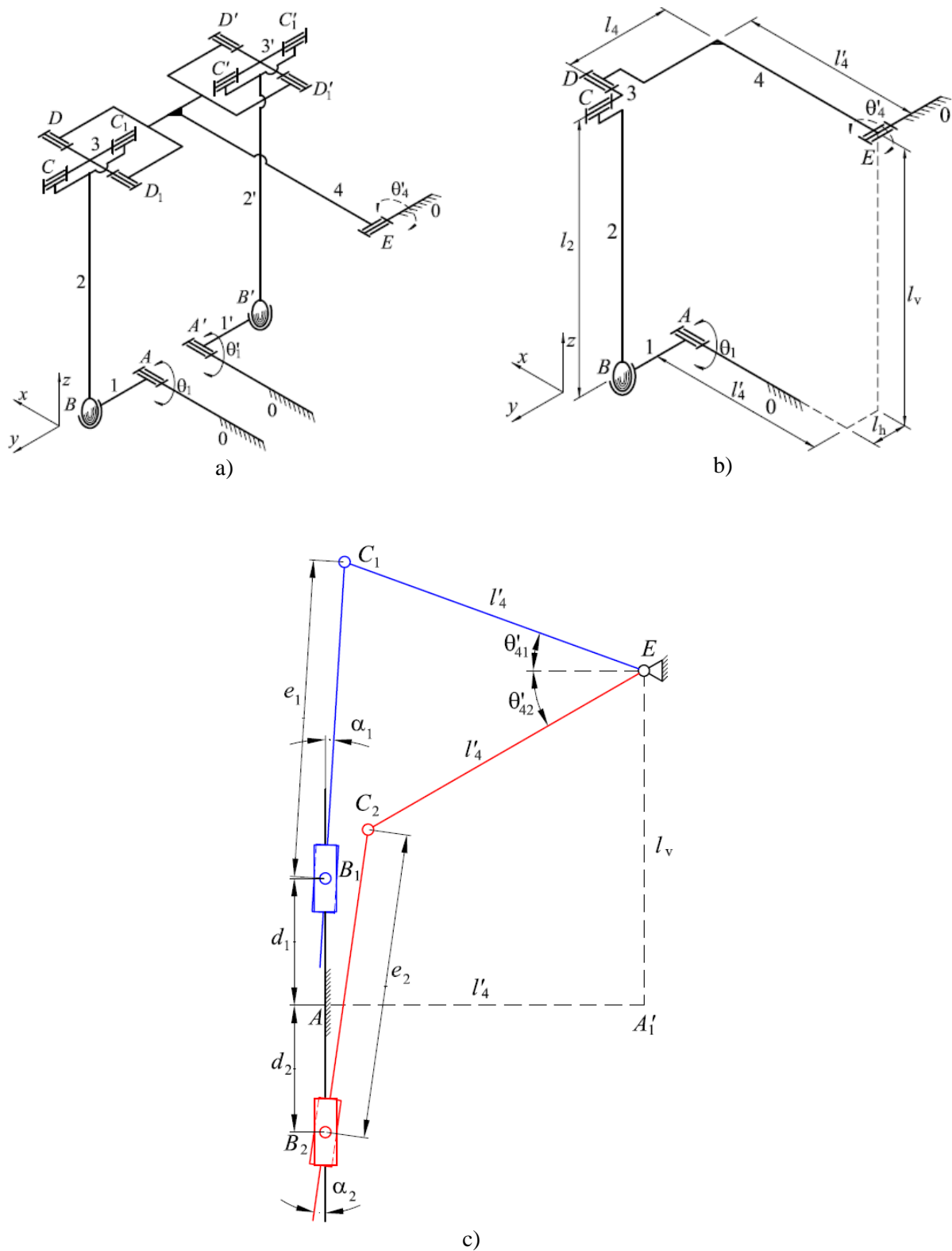
$$l'_4 = \frac{(d_1 - l_v) \sin \theta'_{41} + \sqrt{(d_1 - l_v)^2 \sin^2 \theta'_{41} - 2(1 - \cos \theta'_{41})[(d_1 - l_v)^2 - e_1^2]}}{2(1 - \cos \theta'_{41})} \quad (8)$$

or

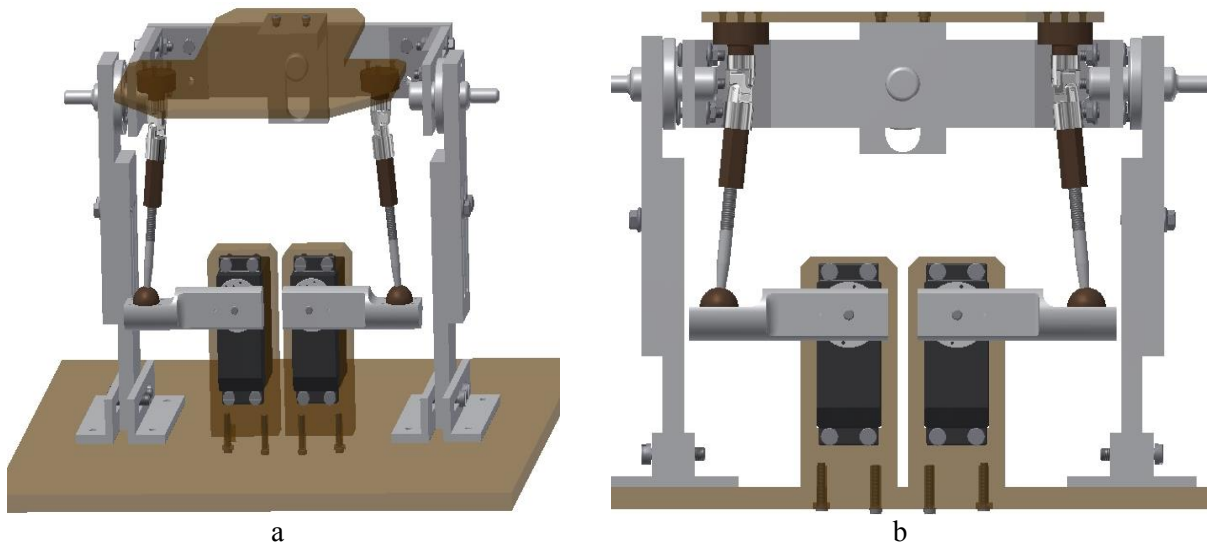
$$l'_4 = \frac{(d_2 + l_v) \sin \theta'_{42} + \sqrt{(d_2 + l_v)^2 \sin^2 \theta'_{42} - 2(1 - \cos \theta'_{42})[(d_2 + l_v)^2 - e_2^2]}}{2(1 - \cos \theta'_{42})} \quad (9)$$

It will be retained the solution that will assure the extreme angular positions of the link 4 for both movements, flexion and extension respectively.

Based on these equations and the already known dimensions we obtain the 3D design, presented in Figure 4. We can observe that actuation is obtained through two servomotors, placed close one to another, corresponding to a small value for dimension  $l_1$ . The length  $l_4$  is chosen based on the anatomical requirements and also offering us plenty of space, so the joints do not affect the position of the foot. The length of the crank  $l_1$ , is established after many simulations to a value that offer us a good torque transmission from the servomotors.



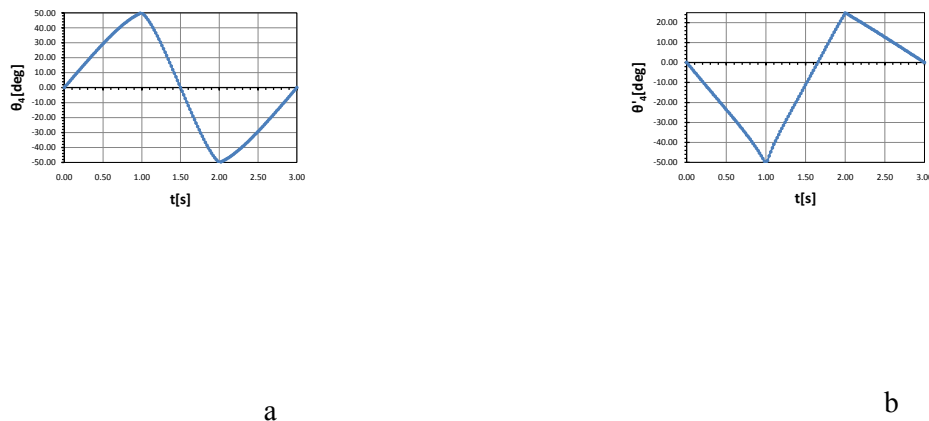
**Figure 3.** Mechanism for flexion/extension movement: a) entire spatial mechanism with two d.o.f.; b) half spatial mechanism with one d.o.f.; c) equivalent planar mechanism with two d.o.f.



**Figure 4.** 3D design of the proposed device: a) isometric view; b) front view

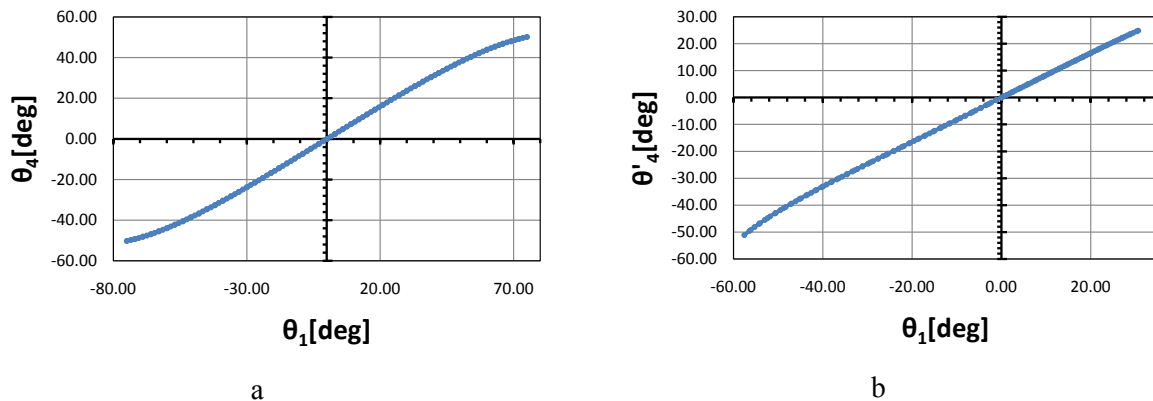
### 3. Simulation results

The dimensions used for simulation and design are:  $l_h = 25mm$ ,  $l_v = 101.5mm$ ,  $l_1 = 60mm$ ,  $l_2 = 103mm$ ,  $l_4 = 75mm$ . We need that the angular strokes for inversion/eversion movement to be 50 degrees for both directions and a range from +20 to -50 degrees for plantar flexion/dorsiflexion movement. In Figure 5 we present the variation of output angle versus time, for a complete movement. Based on this variation we obtain the variation of the input angle  $\theta_1$  according to the required output angle  $\theta_1 = f(\theta_4)$ .



**Figure 5.** Variation of output angle versus time: a) inversion-eversion movement; b) flexion-extension movement

We can observe an almost linear behavior for both required motion (Figure 6a for inversion-eversion movement and Figure 6b for flexion-extension movement). The resulted values can be used to control the servomotors precisely. The height of the system has a critical influence over the whole rehabilitation device. Any change of the height value will increase the possibility of singularities and will modify the value of  $\theta_1$  angle.



**Figure 6.** Variation of output angle versus input angle: a) inversion-eversion movement; b) flexion-extension movement

### 3. Conclusion

In this paper a simple solutions of ankle rehabilitation platform has been proposed, based on two spatial four bar mechanisms. The solution has two degrees of freedom, in order to offer the two required movements for a complete recovery of the injured ankle. The optimization solutions and its 3D design are presented in this paper, together with some simulation results. Based on this simulation, we may conclude that there is an almost linear variation relation between input and output angles. The control strategies and sensing layer will be discussed in future work.

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