Proceeding Paper

Development of a Nonmotorized Mechanism for Ankle Rehabilitation [†]

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Abstract: The objective of this paper is to present the development of a novel nonmotorized mechanism for ankle rehabilitation. The mechanism is based on the four-bar linkage. The mechanism transmits angular movement generated by the patient's hand to an oscillatory movement on the ankle joint. The design of the device used a differential evolution algorithm to find the mechanism dimensions. To validate the system, a virtual tridimensional model was constructed to verify the angular outputs, check the existence of singularities, and execute movements with a virtual wooden test dummy.

Keywords: four-bar linkage; rehabilitation systems; lower limb; ankle; singularity analysis

1. Introduction

Robotics has a wide area of application within which it can include the development of equipment for the rehabilitation of the human body for different types of patients with neurological problems [1,2]. Brain injuries can impair the necessary movements of the lower limb, influencing human gait [3,4]. The use of robotic structures can generate benefits such as reducing costs with active labor for movement-based rehabilitation treatments, as well as expanding the range of exercises performed helping patients to maintain mobility through continuous therapy [5].

The objective of this paper is to develop a non-motorized device for the rehabilitation of the human ankle. Equivalent devices are available on the market, but are motorized [6]. The system proposed in this paper aims to explore a purely mechanical mechanism, hoping to obtain a system easily operated by patients and health professionals. Being a purely mechanical mechanism, the costs of the equipment with actuators and control systems are reduced. It is noteworthy that being a purely mechanical device, the system can be more robust and easier to handle.

The actuation of the mechanism proposed in this paper is performed by the driving force of the patient's upper limb. In this way, is possible to stimulate both the upper and lower limbs. In [7,8] it were shown that self-operated systems can generate positive effects in terms of mobility in the treatment of brain injuries.

In this way, this paper seeks to associate the advantages of using a nonmotorized structure and self-operated to accelerate the recovery process of patients with possible mobility gains in the upper and lower limbs applied to the ankle.

This work is divided into a brief review of the kinesiology of the human ankle followed by mathematical modeling of the device and three-dimensional simulations in CAD/CAE software, finishing with the conclusions.

2. Ankle Kinesiology

The movements of the ankle joint are: plantar flexion and dorsiflexion, occurring in the sagittal plane; abduction/adduction occurring in the transverse plane and inversion/eversion, occurring in the frontal plane [9,10].

The ankle ranges of motion are characterized by a significant variability between the individual in function of geographical/cultural differences, anatomical structures, and different ways to measure the angles [11].

In this paper are used the limits to the dorsiflexion movement goes from 0° to 30°, Figure 1a and the plantar phase from 0° to 50°, Figure 1b. The abduction/adduction has a range of ±10° and the inversion/eversion of ±12° [11].

The main action of the ankle joint is to allow dorsiflexion and plantar flexion of the foot, used to design the proposed novel ankle device [12].
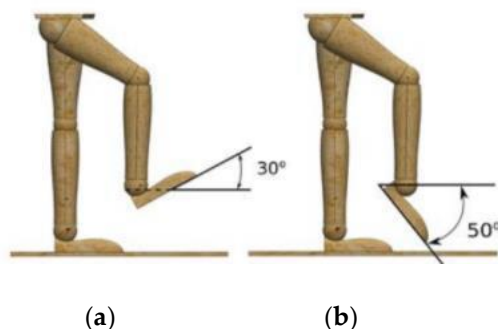

(**a**)   (**b**)

Figure 1. Ankle flexion. (**a**) Dorsiflexion movement; (**b**) plantar flexion movement.

3. Mathematical Model of the Ankle Device

To design the mechanism for ankle rehabilitation, the analytical method was used to find the dimensions that make it possible to obtain the angular output of the ankle flexion joint, as well as to ensure that the stresses produced are supported by the components.

The method based on static balance for planar four-bar mechanisms [13] was used considering that the movement performed has low velocity and acceleration due to the nature of the rehabilitation exercises.

The goal of the desired mechanisms is the conversion of a complete angular movement input from the patient's hand to an oscillatory angular movement output in the lower limb ankle joint to be exercised. Therefore, a four-bar linkage crank-rocker is selected.

The bars and angles of a four-bar linkage model are shown in Figure 2. The angle θ_2 must have a full angular amplitude, i.e., it can reach 360° for rotation, and the angle θ_4 must match the angular amplitude of the ankle joint, defined in Figure 1.
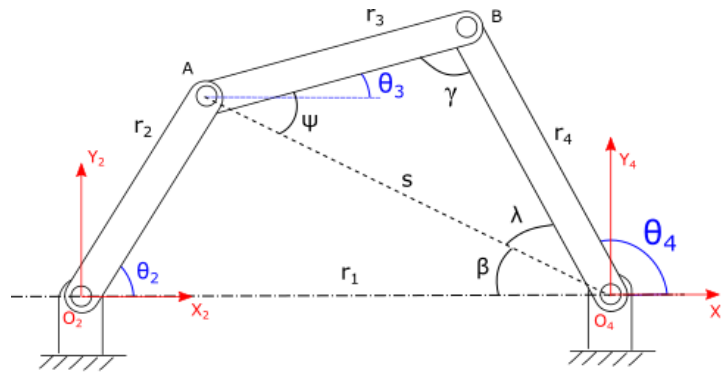
Figure 2. Notation adopted for bars and angles of a four-bar linkage.

The geometric relations are obtained using the cosine's law and are described in (1) to (5).

$$s = \sqrt{r_1^2 + r_2^2 - 2r_1 r_2 \cos \theta_2} \tag{1}$$

$$\beta = \cos^{-1}\left[\frac{r_1^2 + s^2 - r_2^2}{2r_1 s}\right] \tag{2}$$

$$\psi = \cos^{-1}\left[\frac{r_3^2 + s^2 - r_4^2}{2r_3 s}\right] \tag{3}$$

$$\lambda = \cos^{-1}\left[\frac{r_4^2 + s^2 - r_3^2}{2r_4 S}\right] \tag{4}$$

$$\gamma = \pm\cos^{-1}\left[\frac{r_4^2 + r_3^2 - s^2}{2r_4 r_3}\right] \tag{5}$$

Using the relations from (1) to (5), angles θ_3 and θ_4, the output of the system can be obtained by applying (6) to (9).

$$\theta_3 = \psi - \beta, \quad 0° \leq \theta_2 < 180° \tag{6}$$

$$\theta_3 = \psi + \beta, \quad 180° \leq \theta_2 < 360° \tag{7}$$

$$\theta_4 = 180° - \lambda - \beta, \quad 0° \leq \theta_2 < 180° \tag{8}$$

$$\theta_4 = 180° - \lambda + \beta, \quad 180° \leq \theta_2 < 360° \tag{9}$$

The length of bars r_1, r_2, r_3, r_4 and the angular output θ_4 are preset on an evolutional function, which varies values for each bar until relations (1) to (5) are satisfied. We constrained the values to obtain a mechanism suitable for a 1.80 m height person.

To obtain consistent values that comply with the constraints listed in (1) to (5), the evolutional algorithm function [14] interacts with a population of 50 length individuals, with lengths varying from 100 to 300 mm, converging into the minimal working lengths.

The obtained lengths are r₁ = 273 mm; r₂ = 104 mm; r₃ = 235 mm and r₄ = 164 mm.

The obtained device is free of singularities and a complete singularity analysis of the structure can be found in [6].

Since the speed and acceleration of rehabilitation exercises are low, we considered a static model for the calculated positions to obtain the forces on each bar to specify its

transversal section. We used an individual of 1.80 m height and 150 kg weight as the external load upper limit, considering a safety coefficient equal to 1.5 to compensate for unconsidered parameters such as structure load variations, bar frictions, orthosis weight, and sudden movements.

The limit of stress on the bars was selected based on the aluminum alloy yield strength of 276 MPa [15].

The maximum stress values of each bar of the designed mechanism and its respectively selected transversal section are presented in Table 1.

Table 1. Stress calculated on bars of the proposed mechanism.

Stress on Bar r_1 (MPa)	Stress on Bar r_2 (MPa)	Stress on Bar r_3 (MPa)	Stress on Bar r_4 (MPa)	Transversal Section (Width/Height/Thickness)
0.86	0.93	1.02	18.60	1/2″ × 1″ × 2 mm

A chain drive to transmit the angular input from the patient's arm to the bar r_2 and reduce the required effort to a comfortable level is added. A scheme of the mechanism is illustrated in Figure 3.
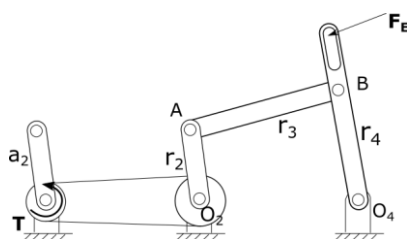

Figure 3. A scheme of the mechanism's design, including an adjustment oblong hole on bar r_4, the receiving patient's leg weight load F_E and a chain-drive transmitting torque T from the patient's hand on bar a_2 to input bar r_2.

4. CAD/CAE Simulations and Results

The Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) models of the proposed device were built and submit them to simulations of the complete cycle of motion.

Figure 4 shows the CAD/CAE model of the proposed device. To simulate the movement of the structure, we used a 3D model of an anthropometrical wooden puppet of 1.8 m height.
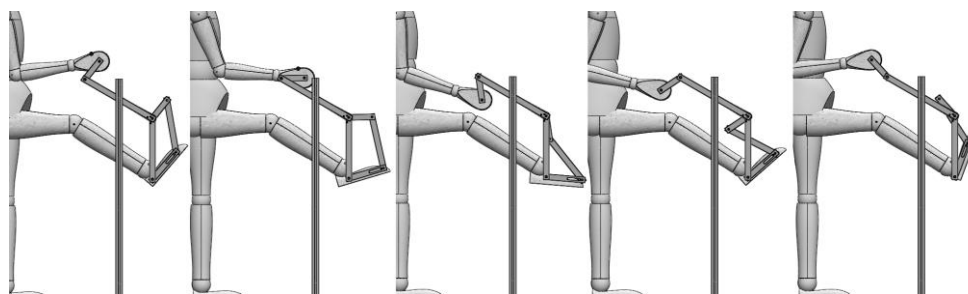

Figure 4. The sequence of images representing the simulation of motion ankle device.

Figure 5 presents the variation of the output angle θ_4 and the angle θ_3 found for the bar lengths obtained for the ankle.

The angular amplitude obtained for the ankle mechanism is 78.89°, against 80° for the joint, with a relative error of 1.39%.

Figure 6 presents the Finite Elements Analysis to the proposed device at the angle θ_2 = 44°. The used aluminum transversal section, Table 1, resisted of the food weight.
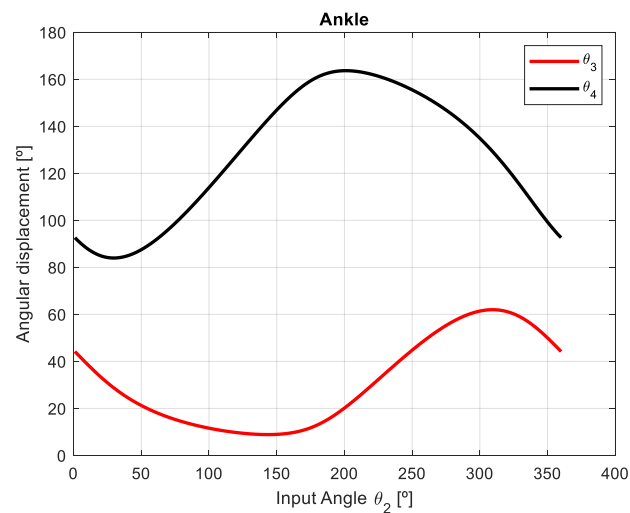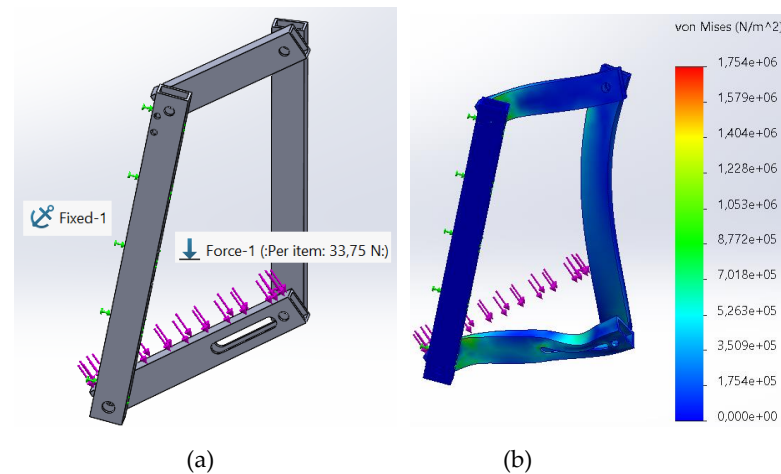
Figure 5. Output angles of the proposed ankle device.

(a) (b)

Figure 6. Finite Element Analysis. (**a**) Initial conditions; (**b**) Stress results.

5. Conclusions

In this paper, a simple, yet innovative design of a crank-rocker mechanism is proposed, combined with a chain-drive transmission, for ankle rehabilitation. This novel structure offers new possibilities to the rehabilitation scenario while being able to assist motor recovery on both upper and lower limbs of the patients, simultaneously.

The proposed device was modeled mathematically and the dimensions were obtained with the aid of an evolutional algorithm.

Static analysis reveals that the structure can be built using light and easy-to-find materials, thus reducing the costs.

The CAD/CAE simulations reveal that the mobility is compatible with the ankle joint movements, while the crank can explore global movements of the upper limb.

The next step will be the construction of the prototype and to realize experimental tests with patients.

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