PRELIMINARY MATHEMATICAL MODEL OF A NEW ANKLE REHABILITATION DEVICE

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Abstract: Among lower limb injuries, the ankle joint is the most common injured in sports and daily life in general. Rehabilitation aims to recover the patient’s physical capabilities through long and repetitive exercises. This paper discusses structural and kinematic aspects of a novel ankle rehabilitation device, which can facilitate the recovery of the ankle joint. The proposed device has two degrees of freedom, and will ensure functionality with minimum dimensions. Some preliminary mathematical models are also presented.

Keywords: ankle rehabilitation, robot, rehabilitation device

1. INTRODUCTION

Statistics show significant increases in the development of robotic devices for non-industrial application. The medical applications are some of the most promising areas of robotics technology, and as a consequence more and more researches are conducted on specialized medicine robots.

Rehabilitation robotics is a special branch of robotics focused on devices that can be used to restore motor control of humans, after a severe physical trauma. Recovery mechatronic systems are evolving, aiming to be a shift from currently used primitive mechanisms to superior technologies that can achieve more accurate restoration of human biomechanics.

The ankle is a limb segment that connects the tibia and fibula of the lower limb with the talus of the foot. These bones are bound together by ligaments and the interosseous membrane. Instability of the ankle joint occurs when the ligamentous and muscular constraints are unable to support the ankle during movement, due to an injury. For a healthy ankle, the normal movements are presented in Figure 1. When the patient moves the top of the foot closer to the tibia, the movement is called dorsiflexion. This motion represents one of the most important functional movements, and it is a vital part for the proper function of the entire kinetic chain. It is used for sitting and standing, also for walking up and down, and requires an adequate range of motion. Plantarflexion is the opposite movement when the bottom of the foot moves away from the tibia [1]. Abduction appears when we move the distal end of the foot away from the midline, or away from the center of the body. Adduction is the opposite motion when the distal end of the foot moves toward the midline. Inversion is the combination movement of abduction and plantarflexion at the ankle complex, where the back of the foot faces the midline of the body. Eversion is the combination movement of abduction and dorsiflexion at the ankle complex, where the back of the foot is directed away from the midline of the body.

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There are several possible types of accidents: fractures, sprains and muscle tears. Regardless of the type of injury, recovery treatment includes three phases:
- treating swelling with ice, rest and anti-inflammatory drugs;
- starting the recovery through exercises that aim to restore joint mobility;
- resumption of sports activities and continuing the recovery exercises.

Several mechanisms have been developed for helping the therapists in the recovery of the ankle. In some recuperation centers, patients still use primitive mechanisms such as elastic bands and foam shapes for balance exercises. There is a tendency of using a programmable robotic system to provide a wide range of exercises, and also to reduce the physical effort due to their repetitive nature and, furthermore, to store the patient’s evolution. To meet this need, several various rehabilitation systems were developed, that can be divided into robotic systems (under the form of parallel mechanisms), orthoses and exoskeletons.

Most encountered rehabilitation parallel mechanisms are Stewart platforms. Some devices use two platforms, one fixed and one mobile, providing three degrees of freedom [2] with various types of actuators, from artificial muscles to brush DC motors.

The ankle-foot orthosis are most common and most used rehabilitation devices for ankle injuries. The main goal of these devices is represented by a reduced weight and ease of operation. They can be powered by a wide range of actuators. For example, Leia [3] is a Lower Limb Exerciser with Intelligent Alloys that has a light structure with two actuators based on NiTi wires. Anklebot [4] is a robotic device mounted on a brace, attached to a custom shoe, allowing the foot to move in different directions, following a preset program. Powered exoskeletons are mainly used for learning gait, but also can be used in recovery, especially for the ankle joint, which supports all human body’s weight. One of the most advanced exoskeleton, BLEEX [5], is used for load-carrying and rehabilitation, where the human provides the control system, while ALEX [6] is used for stroke survivors, the weight of the device is supported by the walker.

In this paper structural and kinematic aspects of a new proposed solution of ankle rehabilitation system, that will be designed to be used for regaining full ankle mobility, are discussed.

2. STRUCTURAL ASPECTS

Based on the normal ankle movements, we want to find two solutions of 2 degrees-of-freedom (DOF) mechanisms, which could recover the plantar flexion/dorsiflexion and inversion/eversion movements. The first one could work as a platform based rehabilitation device, and the second one as a wearable device.
A platform-based ankle rehabilitation device has a link connected to the ground and thus it cannot be used during gait training [7]. There are many proposed projects, and most of them are using parallel mechanisms to reduce the size of the devices [8]. Except the Stewart platform-based device, which is able to offer 6 DOF, most of the other solutions offer 2 or 3 DOF.

If we consider the last link of the mechanism, which has to support the foot, in our case it should have 2 DOF. It means that it can be connected to the fixed link through a universal joint (Figure 2). To drive the 2 DOF moving platform we may use an underactuated 3-SPS/U mechanism (Figure 3.a) or a 2-SPS/U mechanism (Figure 3.b) but we propose a 2-UPU/U mechanism, to avoid additional movements of the links (rotation of the SPS legs around their axes), which is not allowed in our case (because of functional reasons).

Instead of using prismatic joints, which require linear (pneumatic or hydraulic) actuators or rotational actuators and mechanical transmissions that should convert rotational motion in linear motion, we will use a two RSU linkages (Figure 4) [9].

The solution proposed in Figure 4.a has a fixed frame (link 0), connected to the ground and also to the shank, and it will be called “platform based version”. For recovering the two mentioned ankle movements, the foot will be placed on the platform 4. The amplitudes of these movements are variable and controlled progressively, in order to avoid ankle injury. In the case of the second solution (Figure 4.b), called “wearable version”, the fixed frame 0 is connected to the shank. In this case, the patient could stand on a chair, and the leg could be suspended.

To compute their degree of mobility, we will use Kutzbach formula [10] for a spatial mechanism. Because not any link of these mechanisms (Figure 4) is rotating around z axis, only five movements are possible. This is why will use the formula:
\[ M = 6(n - 1 - j) + \sum_{i=1}^{j} f_i, \]  

(1) 

where: \( n \) is the number of links (including the frame); \( j \) is the number of kinematic pairs (joints); \( f_i \) represents the degrees-of-freedom of the \( i^{th} \) kinematic pair. 

For our mechanism, \( n = 9, j = 10 \) (8 rotational joins with \( f = 1 \) and 2 spherical joints with \( f = 3 \)). It means,

\[ M = 6(9 - 1 - 10) + 8 \cdot 1 + 2 \cdot 3 = 2 \text{ DOF}, \]  

(2) 

which means that we need two actuators to drive the mechanism (\( A \) and \( A' \) joints in Figure 4).
3. PRELIMINARY MATHEMATICAL MODEL

The platforms shown in Figure 4 have 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 \( \theta_4 \) 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 \( \theta_4 \) angle, around \( y \) axis, producing plantar flexion-dorsiflexion movement.

Let us considering the first case mentioned above (when both actuated links are rotating with the same angle \( \theta_1 = \theta_1' \)). The simplified mechanism that could offer this movement is shown in Figure 5.a. Even if this mechanism has two actuated links, it could work using a single motor, the second one being redundant. If the two motors are not controlled as \( \theta_1 = \theta_1' \), the mechanism will be blocked.

To write inverse kinematics, an equivalent mechanism, using a single motor, will be considered as shown in Figure 6.a. Because it is a planar linkage, spherical joint \( B \) could be replaced by a rotational one (see Figure 6.b). The position loop closure equation can be written as following:
\[ \overline{T}_1 + \overline{T}_2 + \overline{T}_4 + \overline{T}_5 + \overline{a} = \overline{0}, \]  \hspace{1cm} (3)

or

\[
\begin{align*}
    l_1 \cdot \cos \theta_1 + l_2 \cdot \cos \theta_2 - l_4 \cdot \cos \theta_4 + a &= 0, \\
    l_1 \cdot \sin \theta_1 + l_2 \cdot \sin \theta_2 - l_4 \cdot \sin \theta_4 - l_2 &= 0,
\end{align*}
\]  \hspace{1cm} (4)

where \( \theta_i \) is the angle measured from the \( y \) axis direction to the \( i \) link axis, being positive if the rotation of this link is clockwise. Solving equations (4) we will get:

\[ \theta_1 = \arctan \left( \frac{u}{\sqrt{t^2 + u^2}} \right) \pm \arccos \left( \frac{-l_4^2 + l_2^2 - t^2 - u^2}{2l_4 \sqrt{t^2 + u^2}} \right), \]  \hspace{1cm} (5)

with \( t = -l_4 \cos \theta_4 + a, \quad u = -l_4 \sin \theta_4 - l_2. \)

The mechanism for plantar flexion-dorsiflexion movement will be studied in future work.

4. CONCLUSIONS

In this paper a simple solution of ankle rehabilitation platform has been proposed, based on the four bar mechanism. The solution has two degrees of freedom, in order to offer the two required movements for a complete recovery of the injured ankle. Only structural analysis and preliminary mathematical model for inversion-eversion movement have been discussed here. The mechanism for plantar flexion-dorsiflexion movement will be studied in future work. Also, their 3D design, some simulations, control aspects and experimental results will be presented in future papers.

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