Simulation of an ankle rehabilitation system based on scotch-yoke mechanism

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Abstract. Due to injuries that occur on the ankle joint, everyday all around the world, more and more rehabilitation devices have been developed in recent years. The prices for ankle rehabilitation systems are still high, thus we developed a new device that we intended to be low cost and easy to manufacture. A model of an ankle rehabilitation device is presented in this paper. The device has two degrees of freedom, for flexion-extension and inversion-eversion move, and will ensure functionality with minimum dimensions. For the 3D model that we design, the dimensions are taken so that the proposed system will ensure functionality but also have a small dimensions and low mass, considering the physiological dimensions of the foot and lower leg.

1. Introduction
The ankle joint is a complex structure with an important role in maintaining the balance of an individual during locomotion. Due to its function as load carrier, the human ankle is frequently injured during sports or daily activities. As a result ankle injuries represent 20%-40% among sports injuries [1,2] and are determined by the kind of tissue injure: bone fracture, ligament sprain, muscle strain or tear. The most common injuries are sprains, caused by overstretching or tearing of ligaments. Ankle rehabilitation is important because the injuries affect our mobility and stability. Hence it is desired to find ways to improve the rehabilitation process for a quick and full recovery.

For conventional ankle rehabilitation there are a number of simple devices, which have been produced until now. Robotics technology can offer a replacement for traditional recovery exercises, from labour-intensive operations to technology-assisted operations. There are various approaches for ankle-foot robotic rehabilitation devices. One of the most typical solutions is to wear active devices such as ankle-foot orthoses (AFOs). Several actuation methods have been employed to obtain active elements. For example solid state motors based on shape memory alloy NiTi have been used for an ankle rehabilitation orthosis [3], as well as brushless DC motors [4]. Powered knee-ankle-foot orthosis uses special designed actuators based on springs [5] and also artificial pneumatic muscles mounted on a carbon fiber frame [6]. Some other actuation methods includes the use of servomotors and torsion springs [7, 8].

Another segment of lower limb rehabilitation devices is represented by parallel mechanisms that have the benefits of high dynamic stiffness. The platforms can possess different degrees of freedom: three [9, 10], four [11] or even six [12, 13] and the exercises are mostly achieved with the help of reality-based programs running on a PC [14].
Powered exoskeletons are mainly used for learning gait at patients that suffer from a stroke, losing their capability of walking. One of the most advanced exoskeleton, BLEEX [15] is used for load-carrying and rehabilitation, while ALEX [16] and LOPES [17] are used for stroke survivors.

2. **Dimensional synthesis and numerical simulation**

The three basic movements of the ankle joint are dorsiflexion (flexion)/plantar flexion(extension), inversion/eversion and abduction/adduction. For a complete recovery of the ankle only two movements are required: flexion/extension and inversion/eversion. The angle range of ankle movements for most people varies as following: plantar flexion, 25 to 50 degree, dorsiflexion, 25 to 25 degrees, inversion 35 to 50 degrees, eversion, 0 to 25 degrees.

Starting from the basic ankle movements two solutions for ankle rehabilitation devices have been proposed: a platform based version, and a wearable version [18]. Both solutions are using rotational actuators and mechanical transmissions that convert the rotational motion in linear motion. The scotch-yoke mechanism is used for its advantages: high torque output, smooth operation. In figure 1 we present the kinematics of the proposed mechanism for the platform-based rehabilitation device, with links $3$ and $3'$ as actuated links.

![Figure 1. Kinematics of the proposed mechanism for a platform-based ankle rehabilitation device.](image)

To achieve the inversion/eversion movement, the links $3$ and $3'$ are rotated with the same angle, $\theta_3 = \theta'_3$ (both in clockwise or counter clockwise direction), while the moving platform 7 will generate the desired motion, with $\theta_7$ angle, around x axis. The equivalent mechanism for this movement (with
one actuated link) is presented in figure 2.a. For the mechanism dimensional synthesis and the inverse kinematics we are using a simplified planar mechanism (see figure 2.b).

\[ (l_7^2 + l_h^2 + l_v^2 + 2l_7(l_v \sin \theta_7 - l_h \cos \theta_7) - l'_2 - l_5) \]

This angle is considerate positive when the platform 7 produces the inversion movement. For the mechanism synthesis we assume that \( l_v, l_h, l_7 \) are known parameters and the \( \theta_3 \) and \( \theta_7 \) angles will be imposed (taking into account the angle range of ankle movements):

\[ l_3 = \left( \frac{l_7^2 + l_h^2 + l_v^2 + 2l_7(l_v \sin \theta_7 - l_h \cos \theta_7)}{l_3} \right)^{1/2} \]

\[ l_2 \geq 2 \cdot l_3 \]

\[ l'_2 = \left( l_7^2 + l_h^2 + l_v^2 - 2l_7l_h \right)^{1/2} - l_5 \]

To achieve the flexion/extension movement the links 3 and 3’ are rotated with the same angle but in different direction, \( \theta_3 = -\theta'_3 \), while the moving platform 7 will generate the desired motion with \( \theta'_7 \) angle, around \( y \) axis. The equivalent mechanism for this movement (with one actuated link) is presented in figure 3. Inverse kinematics for this mechanism leads to \( \theta_3 \) angle (positive when the platform 7 generates the dorsiflexion movement) [20]:
\[
\theta_3 = \arcsin \left[ \frac{\sqrt{l_3^2 + l_6^2 + l_7^2 + 2 \cdot l_7 \cdot (l_v \cdot \sin \theta_7 - l_h \cdot \cos \theta_7) - l_2^2 - l_5^2}}{l_3} \right]
\] (5)

**Figure 3.** Equivalent mechanism for plantar flexion-dorsiflexion movement: (a) with two actuated links; (b) with one actuated link

Based on the previous equations, we will simulate the variation of the \( \theta_3 \) angle, for both motions. The known dimensions have been chosen based on the human anthropomorphic dimensions and space requirements. For the first diagram we consider the following dimensions (in mm): \( l_7 = 65 \), \( l_h = l_7 \), \( l_v = 200 \), \( l_7 = 75 \). Because the mechanism is designed for both legs, we need that the angular strokes of \( \theta_7 \) (inversion/eversion movement) to have maximum amplitude of 50 degrees for both directions, while the \( \theta'_7 \) angle (flexion/extension movement) will vary between +20 and -50 degrees.

**Figure 4.** Numerical simulation results of angles versus time: (a) inversion/eversion movement; (b) flexion/extension movement
After the calculation, we get the following values for the unknown parameters (in mm): \( l_3 = 49 \), \( l'_2 = 102 \), \( l_5 = 98 \). In figure 4, we present the variation of \( \theta_3 \), \( \theta_7 \) and \( \theta'_7 \) angles according to time. It is observable the nonlinear behavior of \( \theta_3 \) angle; for the inversion/eversion movement the mechanism is blocked at 45 degrees (figure 5.a); for the flexion/extension movement the mechanism is blocked at -40 degrees (figure 5.b).

![Figure 5](image)

**Figure 5.** Numerical simulation results of \( \theta_3 \) angle function of output angle:
(a) inversion/eversion movement; (b) flexion/extension movement

Given these considerations, new dimensions for the links are required. The new imposed values are (in mm), \( l_7 = 80 \), \( l_v = 180 \), \( l_b = l_7 \), \( l'_7 = 75 \) and the following values have been obtained, \( l_3 = 60 \), \( l'_2 = 60 \), \( l_5 = 120 \). In figure 6 the variation of the input and output angles versus time are presented. It is observable that the variation of \( \theta_3 \) angle according to \( \theta_7 \) and \( \theta'_7 \) is almost linear, aspect that will simplify the motion control of the device.

![Figure 6](image)

**Figure 6.** Numerical simulation results of angles versus time, for the new dimensions:
(a) inversion/eversion movement; (b) flexion/extension movement
3. Conclusions
In this paper, a simple solution of ankle rehabilitation platform has been proposed, based on the simple scotch-yoke mechanism. The solution has two degrees of freedom, in order to offer the two required movements for a complete recovery of the injured ankle. Some structural and kinematic aspects, along with simulation results are presented in this paper. Control aspects and experimental results will be presented in future papers.

4. References
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