Ankle rehabilitation device with two degrees of freedom and compliant joint

C-M Racu (Cazacu)¹ and I Doroftei¹
¹ “Gheorghe Asachi” Technical University of Iasi, Mechanical Engineering, Mechatronics and Robotics Department, Blvd. D. Mangeron, No. 43, 700050 - Iasi, Romania
E-mail: cristina.racu@tuiasi.ro

Abstract. We propose a rehabilitation device that we intend to be low cost and easy to manufacture. The system will ensure functionality but also have a small dimensions and low mass, considering the physiological dimensions of the foot and lower leg. To avoid injure of the ankle joint, this device is equipped with a compliant joint between the motor and mechanical transmission. The torque of this joint is intended to be adjustable, according to the degree of ankle joint damage. To choose the material and the dimensions of this compliant joint, in this paper we perform the first stress simulation. The minimum torque is calculated, while the maximum torque is given by the preliminary chosen actuator.

1. Introduction
Ankle joint is an articulation with a special importance in keeping the balance of an individual, during gate or stance position. According to some studies [1] an important number of people around suffer from sprains of fractures of the ankle every year. In this articulation occur multiple movements, thus a higher rate of injuries. For a normal life it is impetuously that the ankle joint is fully recovered, and the need of recovery exercises emerges. We can divide the devices used for ankle rehabilitation in three categories: parallel mechanism robots, prostheses and powered orthoses and powered exoskeletons. From Yoon, et. al. [2] we find a parallel reconfigurable robot , which has a large range of various exercises. This robot can allow desired ankle and foot motions, four degrees of freedom and it’s driven by pneumatic actuators. A soft parallel ankle rehabilitation robot, with four air artificial muscle as actuators, was developed by P.K. Jamwal and his collaborators [3]. This device provides three rotational degrees of freedom to the ankle joint for the necessary range of motion and muscle strengthening exercises. “Rutgers Ankle” [4, 5] is a Steward platform-type haptic interface, which supplies six degrees of freedom. This platform allows patients to exercise at home, true an online database that can be easily accessed by the therapist.

A Lower Limb Exerciser with Intelligent Alloys (Leia) [6] was developed by S. Pittaccio, and it is an orthosis, composed of aluminum structure spanning above and below the ankle joint. It as a pair of motors based on shape memory alloy NiTi, obtained a 40º movement by coiling the wire along a spiraling sequence of pulleys. Anklebot [7], is a wearable therapeutic robot designed by engineers at MIT’s Newman Laboratory for Biomechanics and Human Rehabilitation. The subject is seated and wears a modified shoe and a knee brace. The recovery is achieved by moving the ankle along a commanded trajectory, while monitoring static torque-angle relation.
Powered exoskeletons are mainly used for learning gait in patients that suffer from a stroke, losing their capability of walking. Although it is used for entire leg (hip, knee, ankle), the exoskeleton is a powerful tool for recovery, especially for the ankle joint, which supports all human body’s weight. A lower extremity exoskeleton [8], named BLEEX, was developed aiming to help people for load-carrying and rehabilitation. His unique design allows the user to control the system, while the exoskeleton provides the required strength. It is equipped with a frame that supports different loads, two powered legs and a power unit. ALEX is an active leg exoskeleton [9], used for stroke survivors, the weight of the device is supported by the walker. It has several joints: two joints at hip (abduction-adduction motion, and sagittal plane motion), revolute knee joint and a revolute joint for vertical rotation. Also, it has a parallelogram mechanism for vertical translation, a back support for the subject, pelvic straps and tight brace.

To meet the need for exercise, several mechanisms have been developed for ankle rehabilitation. Traditionally are still used primitive passive mechanisms such as elastic bands, zigzag staircase, and foam roll for balance exercises. However, these mechanisms allow only simple exercises that require patient effort and cannot store information about its progress [10]. Although a variety of systems used in recovery of ankle joint exist [17], we can say that currently we still need a system that fully satisfies the needs of the patient. Therefore, there is a request for easy to use mechatronic systems that facilitate optimal recovery of patients, suffering from various diseases of the ankle. Our system provides a new actuation layer, based on the simple scotch-yoke mechanism, conducting to small dimensions, reduced weight and simple commands.

2. Proposed Ankle Rehabilitation Device

In designing the rehabilitation system, we assumed that the device must provide dorsiflexion and plantar flexion movements and pronation and supination rotations, necessary for a complete recovery of the ankle joint [11]. The kinematics of the new device is presented in figure 1.a, while in figure 1.b the 3D design of the mechanism is presented. This device is based on the simple scotch-yoke mechanism and it consists in a plate connected to a fixed frame through cardanic joints.

![Figure 1. The proposed rehabilitation system: a) kinematics; b) 3D design.](image-url)

The actuation of the system is achieved through servomotors, connected to a lever that actuates the scotch-yoke mechanism. For saving space, we placed the scotch-yoke mechanisms facing each-other. Thus, for plantar flexion-dorsiflexion movement, we will rotate the motors with the same angle, in the same direction. Rotating the motors with the same angle, but different direction will provide us the inversion-eversion movement. The rotational movement is transmitted from the motor shaft through a
servo arm (see figure 2.a detail) and passed to a special designed flange. A torsion spring, which is our compliant link, is coupled to the flange and to the rotational arm. By measuring the spring deflection, the joint torque can be measured directly. For that we will need an experimental calibration. It means, we will only need a calibrated spring and an encoder, to measure the rotational movement and the torque.

The spring design was implemented by S. Wang et al. [14] in their optimization of an exoskeleton joint, and it consists of two connected Archimedean spirals (see figure 2b). Given the length of the lever arm, we impose a parameter \( r_2 = 62 \text{ mm} \). The difference between \( r_1 \) and \( r_2 \) represent the spiral thickness, while \( b \) is the spring width. Each of the spirals has an active coil number \( n = 1 \). The stress distribution and displacement are checked using finite element analysis tool (Solidworks 2014).

Figure 2. Compliant joint: a) 3D view of the subassembly; b) planar views of the compliant link.

3. Stress Analysis

According to Divecha H M [13], an equation for static forces acting on ankle joint in mid-air horizontal suspension can be determined, offering us the resulting joint reaction force of 15 N. Other estimations of forces and moments of lower limb joints offer us a vertical force, for a standing man, of approximately 20 N [14]. Another study, performed by D. Fong et col. [15], consisting in calculating the ground reaction forces through pressure insole data, offer us a range force of 11.79 N for medial-lateral direction and 33.53 N for anterior-posterior direction, for a male subject walking and running. Thus, in our study, we impose an initial force of 10 N, the force that the system must overcome to insure rehabilitation.

Figure 3. Analyze of the scotch yoke mechanism.

Analyzing the scotch yoke mechanism (figure 3), using the principle of virtual work [16] we find the reaction forces, and the required torque:
For our system $r_1$ is the length of the lever arm and $F$ is the force exercised by the foot. Thus, in our case $r_1 = 75\ mm$, $\theta = 50^\circ$ and $F = 10\ N$. The minimum torque, necessary to actuate a healthy ankle joint is now:

$$T = -75 \cdot \sin(50) \cdot 10 = 0.575\ N \cdot m$$  \hspace{1cm} (1)

The maximum torque provided by a preliminary chosen motor is $T = 2.35\ N \cdot m$. For the Finite Element Analysis we propose two materials to be considered. The first material adopted from program’s library is steel AISI 1020 with elastic modulus of $200\ 000\ N/mm^2$ and Poisson’s ratio of 0.29. The second material is Acrylonitrile butadiene styrene (ABS) plastic with elastic modulus of $2000\ N/mm^2$ and a Poisson’s ratio of 0.394.

Because the spring must always remain in the elastic deformation domain, a Von Mises stress analysis was performed. Spatial state of stress for simulation is given by the relation:

$$\sigma_{eh} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_x - \sigma_z)^2 + (\sigma_y - \sigma_z)^2 + 6\tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2}$$  \hspace{1cm} (1)

The spring was deformed by minimum and maximum torque, providing us the total deflection. The boundary conditions imposed to the spring are: fixed extremities, torque applied in the center. For the initial test, we choose following dimensions: spiral thickness $r_2 - r_1 = 4\ mm$ and spring width $b = 10\ mm$. For the minimum value of torque we find the following results:
- alloy steel maximum displacement 0.051 $mm$ (figure 4 a);
- ABS maximum displacement 4.662 $mm$ (figure 4 b).

Due to the fact that alloy steel displacement was so small, the material choosed for analysis is ABS. This material indentifies a family of engineering thermoplastics, low cost, with a broad range of performance characteristics and easy to machine and fabricate. The most important mechanical properties of ABS are impact resistance and toughness, and it is an ideal material for structural applications when strength and stiffness are required. The material can take complex shapes, through 3D printing, and has good mechanical characteristics, thus making it suitable for our application. Yield strength, or the yield point, is defined as the amount of stress that a material can undergo before moving from elastic deformation into plastic deformation. The ultimate tensile strength for ABS (the limit stress at which the material breaks with sudden release of the stored elastic energy) was found to be around 40 MPa [18]. The initial dimensions were too small and the value of ABS displacement was high, thus we modify the dimensions. Our goal is to dimension the spring so we can have from ABS a minimum value, less than 1 $mm$ of displacement, at a minimum torque. The first step was to increase the spiral thickness to $r_2 - r_1 = 6\ mm$ and to increase the spring width $b = 20\ mm$. 

\[
\begin{bmatrix}
F_{34} \\
F_{14} \\
F_{23} \\
F_{12} \\
T
\end{bmatrix} =
\begin{bmatrix}
r_1 \\
r_{1a} \\
F \\
0 \\
F \\
0 \\
-r_2 \cdot \sin \theta \cdot F
\end{bmatrix}
\]  \hspace{1cm} (1)
By applying both minimum and maximum torque we find the following results:
- minimum torque- maximum displacement 0.711 mm (figure 4c);
- maximum torque- maximum displacement 2.81 mm.

The maximum value for Von Mises stress at minimum torque was 4.232 MPa (figure 5.a) , while at maximum torque, for these dimensions, was found to be 16.9 MPa.

Although the displacement found value for minimum torque is small, we propose a further development of the spring, increasing, once again, the spring width. The new values found for minimum and maximum torque are:
- minimum torque- maximum displacement 0.454 mm (figure 5c );
- maximum torque- maximum displacement 1.854 mm.

The Von Mises stress for minimum torque is 2.734 MPa (figure 5b) and for maximum torque is 11.176 MPa, safe within the limits. Further development of the spring will determine angular deflection, and calibration.

**4. Conclusions**

In this paper we present a novel ankle rehabilitation device with two degrees of freedom, which is using a double spiral spring as a compliant link. The compliance is necessary to avoid ankle joint injure, during rehabilitation. In this paper we performed the first stress simulation of the compliant
joint. Optimal width at minimum torque of 0.575 $N*m$ and a spiral thickness of 6 $mm$ was found to be 30 $mm$. Some angular deflection and calibration will be studied in future work.

Acknowledgement
This work was supported by the strategic grant POSDRU/159/1.5/S/133652, co-financed by the European Social Fund within the Sectorial Operational Program Human Resources Development 2007 – 2013.

References
[1] Waterman B, Owens B, Davey S, Zacchilli M and Belmont Jr P J 2010 The epidemiology of ankle sprains in the United States The Journal of Bone & Joint Surgery 92 pp 2279-2284p
[2] Yoon J, Ryu J and Lim K B 2005 A novel reconfigurable ankle rehabilitation robot for various exercises Robotics and Automation pp 2290-2295
[3] Jamwal P K, Xie S, Aw K C 2009 Kinematic design optimization of a parallel ankle rehabilitation robot using modified genetic algorithm Robotics and Autonomous Systems 57 pp 1018-1027
[4] Girone M, Burdea G, Bouzit M, Popescu V and Deutsch J E 2001 A Stewart platform-based system for ankle tele-rehabilitation Autonomous Robots 10 pp 203-212
[5] Boisan R F, Lee C S, Deutsch J E, Burdea G C and Lewis J A 2002 Virtual reality-based system for ankle rehabilitation post stroke Proc. 1st Int. Workshop Virtual Reality Rehabilitation pp 77-86
[6] Pittaccio S and Viscuso S 2011 An EMG- Controlled SMA device for the rehabilitation of the ankle joint in post-acute stroke Journal of materials engineering and performance 20 pp 666-670
[7] Lee H, Ho P, Rastgaar M A, Kregbs H I and Hogan N 2011 Multivariable static ankle mechanical impedance with relaxed muscles Journal of Biomechanics 44 pp 1901-1908
[8] Kazerooni H, Racine J L, Huang L and Steger R 2005 On the control of the Berkeley lower extremity exoskeleton (BLEEX) International Conference on Robotics and Automation pp 4353-4360
[9] Banala S K, Hun Kim S, Agrawal S K and Scholz J P 2009 Robot assisted gait training with active leg exoskeleton (ALEX) Neural Systems and Rehabilitation Engineering 1 pp 2-8
[10] Dai J S, Zhao T and Nester C 2004 Sprained ankle physiotherapy based mechanism synthesis and stiffness analysis of a robotic rehabilitation device Autonomous Robots 16 pp 207-218
[11] Racu (Cazacu) C M and Doroftei I 2014 Structural and kinematic aspects of a new ankle rehabilitation device Applied Mechanics and Materials 658 pp 507-512
[12] Wang S, Meijneke C and van der Kooij H 2013 Modeling,design and optimization of mindwalker series elastic joint IEEE Int Conf Rehabilitation Robotics
[13] Dicheva H Static analysis of the ankle joint (Cardiff School of Engineering)
[14] Chowdhury S and Kumar N 2013 Estimation of forces and moments of lower limb joints from kinematics data and inertial properties of the body by using inverse dynamics technique Journal of Rehabilitation Robotics pp 93-98
[15] Fong D, Hong Y, Yung P, Fung K Y, Lao M and Chan K M 2006 Estimating complete ground reaction forces and ankle joint torques from pressure insole data in walking and running XXIV ISBS Symposium (Salzburg: Austria)
[16] Trabia M Analyze of the scoth yoke mecanism, using the principle of virtual work Howard R ed (Hughes College of Engineering: Nevada)
[17] Racu (Cazacu) C M and Doroftei I 2014 An overview on ankle rehabilitation devices Advanced Materials Research 1036 pp 781-786
[18] In site http://teststandard.com/data_sheets.htm