# STRUCTURAL AND KINEMATIC ASPECTS OF A NEW ANKLE REHABILITATION DEVICE

PhD. Stud. Eng. Racu (Cazacu) C.[1], Prof. Dr. Eng. Doroftei I.[2]
Faculty of Mechanical Engineering – "Gheorghe Asachi" Tehnical University of Iasi, Romania [1,2]

[1]cristina.racu@tuiasi.ro , [2]idorofte@mail.tuiasi.ro

***Abstract:*** *The goal of this paper is to propose a new ankle rehabilitation platform, which can realize a large range of ankle related foot movements. In designing the rehabilitation system, we assume that the device must provide dorsiflexion/plantar flexion and inversion/eversion movements, necessary for complete recovery of the ankle joint. Therefore the system must be spatial oriented (rotations around two perpendicular axes, hence two degrees of freedom). The device should aim to achieve low cost, low weight and ease of practical realization of the device. We present structural and kinematic aspects of the proposed device for ankle rehabilitation.*

**Keywords**: ANKLE REHABILITATION, KINEMATICS, ROBOTIC DEVICE

## *1. Introduction*

The ankle joint forms a junction between the leg and the foot, turned into a horizontal mobile platform, adaptable to irregularities of the surface. Due to its important role in human locomotion, the ankle is the most injured segment of the lower limb. Ankle injuries can be divided into ligament tears, fractures and sprains (last one is the most encountered). Higher rates of ankle sprain appear to men between 15 and 24 years old, and also woman over 30 have higher rates than men [1]. Most ankle injuries occur either during sports activities or while walking on an uneven surface that forces the foot and ankle into an unnatural position.

The treatment of any injury of this articulation consists in 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 recuperations 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 [2]. Some devices use two platforms, one fixed and one mobile, providing three degrees of freedom [3] with various types of actuators, from artificial muscles to brush DC motors. Most common and used rehabilitation devices for ankle injuries are ankle-foot orthosis. The main purpose of these devices is to achieve low weight and ease of operation. They can be powered by a wide range of actuators [4,5]. 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.

For a healthy ankle, normal movements are presented in figure 1. For most people, the angle range of ankle movements varies as following: plantar flexion, 25 to 50 degrees; dorsiflexion, 20 to 25 degrees; inversion, 35 to 40 degrees; eversion, 0 to 25 degrees; adduction, 25 to 30 degrees; abduction, 25 to 30 degrees [6].

Starting from the basic ankle movements, we propose a 2 DOF mechanism, which could recover the plantar flexion/dorsiflexion and inversion/eversion movements.

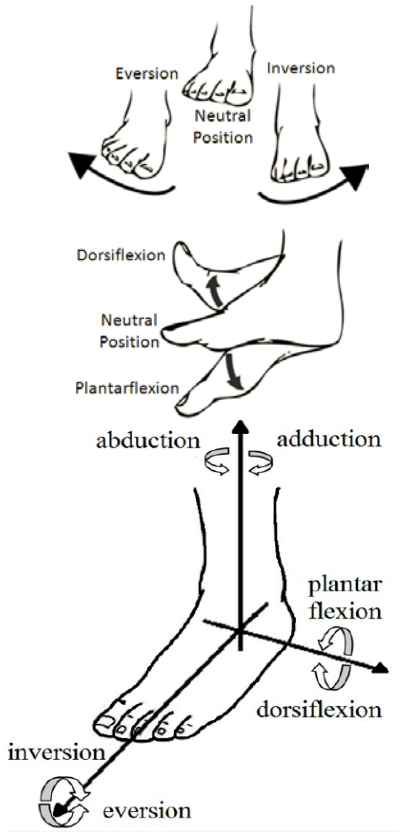



***Fig. 1.*** *Normal ankle movements*

## *2. Structural aspects*

Our goal is to find light weight, low cost and easy to manufacture solutions for ankle rehabilitation platforms. The proposed solution should consider offering the two movements (flexion-extension and inversion-eversion) necessary for a complete recovering of the injured ankle, resulting in two degrees of freedom.

We propose a solution, based on simple four bars mechanism, presented in Fig. 2. This device has a fixed frame (link 0) connected to the ground and also to the shank. The foot will be placed on the plate 4 and the ankle joint will be forced to be recovered for the two mentioned movements. The actuated links are 1 and 1' and the plate 4 is the driven link. If we rotate links 1 and 1' with same angle, $\theta_1 = \theta_1^{'}$ (both in clockwise or counterclockwise direction), the plate 4 will be driven with $\theta_4^{'}$ angle, producing the flexion-extension of the ankle joint.

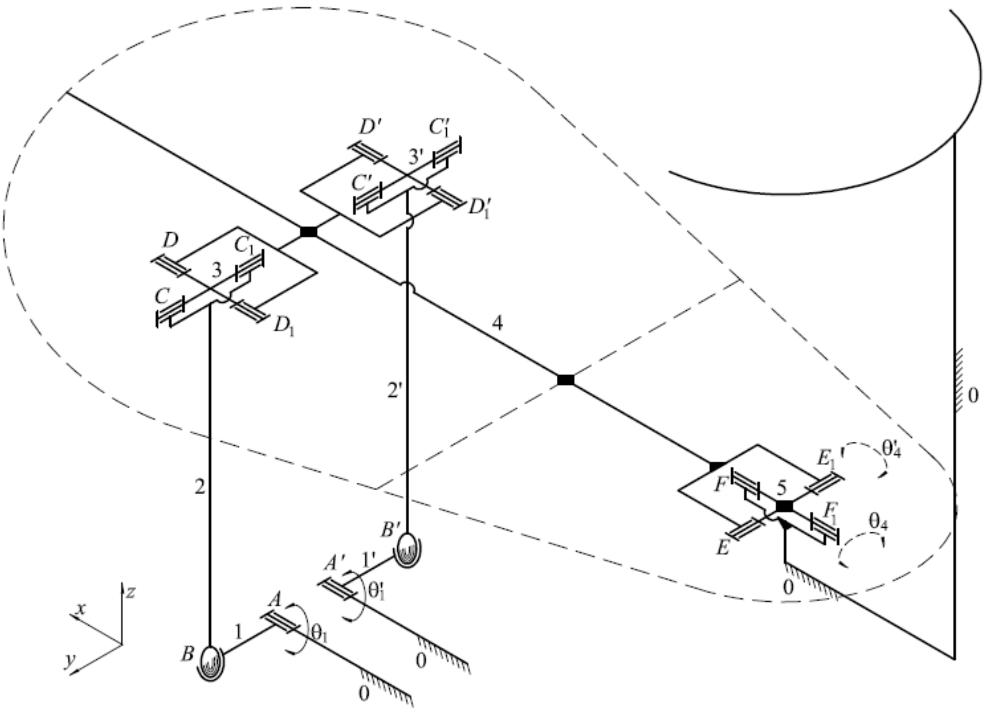



***Fig. 2.*** *Kinematics of the proposed mechanism, for a platform-based version*

If these mentioned links are rotated with the same angle but in opposite direction, $\theta_1 = -\theta'_1$ the plate 4 will be driven with $\theta_4$ angle, producing the eversion-inversion movement.

To compute the degree of mobility, we use Kutzbach formula for a spatial mechanism:

$$M = 6(n-1-j) + \sum_{i=1}^{j} f_i \,, \qquad (1)$$

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 two spherical joints with $f$ = 3). It means,

$$M = 6(9-1-10) + 8\cdot 1 + 2\cdot 3 = 2 \;\; DOF \,, \qquad (2)$$

which means that we need two actuators to drive the mechanism (*A* and *A'* joints in Fig. 2).

## *3. Kinematic aspects*

The link 4 from our mechanism will support the sole, which has to be fixed (through some belts) on it. As we mention before, 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. 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 [7].

In figure 3 we present the equivalent decoupled mechanisms for both inversion-eversion movement (a) and flexion-dorsiflexion movement (b).

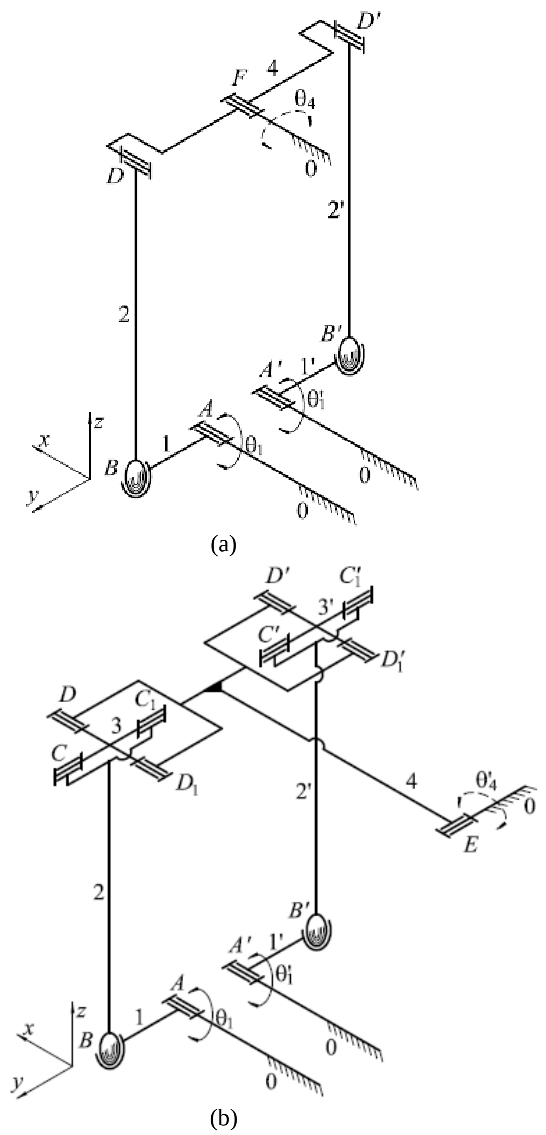



***Fig. 3.*** *Equivalent decoupled mechanisms: a) for inversion-eversion movement; b) for flexion-dorsiflexion movement*

For the inversion-eversion movement (Fig 3.a) the simplified mechanism has two actuated links, but it could work using a single motor, the second one being redundant. The main condition for the correct operation of this mechanism is to impose the control of the motors as $\theta_1 = \theta_1^{'}$, or else the mechanism will be blocked.

To write inverse kinematics, an equivalent mechanism, using a single motor, will be considered (see Fig. 4). The position loop closure equation can be written as following

$$\overline{l_1} + \overline{l_2} + \overline{l_4} + \overline{l_2} + \overline{a} = \overline{0}, \qquad (3)$$

or

$$\begin{cases} l_1 \cdot \cos\theta_1 + l_2 \cdot \cos\theta_2 - l_4 \cdot \cos\theta_4 + a = 0 \\ l_1 \cdot \sin\theta_1 + l_2 \cdot \sin\theta_2 - l_4 \cdot \sin\theta_4 - l_2 = 0 \end{cases}, \qquad (4)$$

where $\theta_i$ is the angle measured from *y* axis direction to the *i* link axis, being positive if the rotation of this link is clockwise.

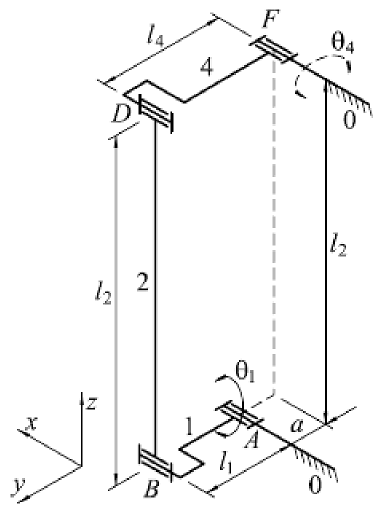



***Fig. 4.*** *Equivalent mechanism with one DOF for inversion-eversion movement*

Solving equations (4) we will get

$$\theta_1 = \operatorname{atan2}\left(\frac{-u}{\sqrt{t^2+u^2}}, \frac{-t}{\sqrt{t^2+u^2}}\right) \pm \arccos\left(\frac{-l_1^2 + l_4^2 - t^2 - u^2}{2l_1\sqrt{t^2+u^2}}\right), \qquad (5)$$

with $t = -l_4 \cos\theta_4 + a,\ u = -l_4 \sin\theta_4 - l_2$.

Let now consider a mechanism with one DOF for plantar flexion-dorsiflexion movement (see Fig. 5). Spherical joint, in this case, may be replaced by an universal joint (see Fig. 6). First, if we apply standard Denavit - Hartenberg convention to this closed-loop mechanism, we get the parameters presented in Table 1. Based on these, we will write the transition homogeneous transformation matrixes that express the position and orientation of the current frame with respect to the previous one. Multiplying all these matrixes we will get the total homogeneous transformation matrix of the mechanism that expresses the position and orientation of the last frame with respect to the referential frame.
The orientation loop closure equation for our mechanism can be written as following

$${}^{0}_{5}R = {}^{0}_{1}R \cdot {}^{1}_{2}R \cdot {}^{2}_{2'}R \cdot {}^{2'}_{3}R \cdot {}^{3}_{4}R \cdot {}^{4}_{5}R = I, \qquad (6)$$

where ${}^{i-1}_{i}R$ is the transition orientation matrix that expresses the orientation of the $\{i\}$ frame with respect to the $\{i-1\}$ frame.

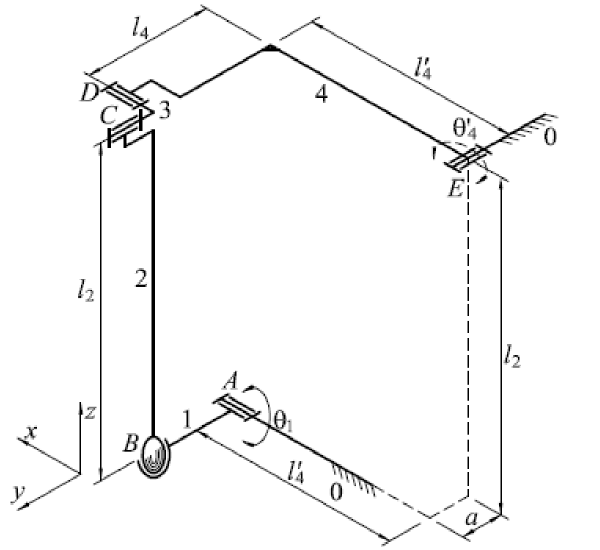
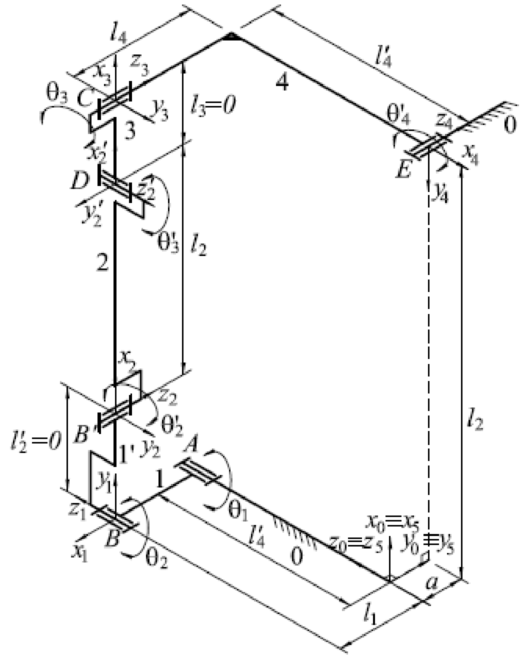



***Fig. 5.*** *Real mechanism for flexion-dorsiflexion movement*




(b)

***Fig. 6.*** *Equivalent mechanism with one DOF for flexion-dorsiflexion movement*

***Table 1.*** *Standard Denavit-Hartenberg parameters*

| Link | $a_i$ | $\alpha_i$ | $d_i$ | $\theta_i$ |
|---|---|---|---|---|
| 1 | $l_1$ | 0 | $l_4^{'}$ | $\theta_1 - \pi/2$ |
| 2 | 0 | $-\pi/2$ | 0 | $\theta_2 + \pi/2$ |
| 2' | $l_2$ | $-\pi/2$ | 0 | $\theta_2^{'}$ |
| 3 | 0 | $\pi/2$ | 0 | $\theta_3^{'}$ |
| 4 | $l_4^{'}$ | 0 | $l_4$ | $\theta_3 + \pi/2$ |
| 5 | $-l_2$ | $\pi/2$ | $-a$ | $\theta_4^{'} - \pi/2$ |

The position loop closure equation can be written as following

$$\overline{r_1} + \overline{r_2} + \overline{r_3} + \ldots + \overline{r_n} = \overline{0}, \qquad (7)$$

where $\overline{r_i}$ is a vector drawn from the origin of the frame $\{i-1\}$ to the origin of the $\{i\}$ frame.

The following equation is obtained according to standard Denavit - Hartenberg convention,

$$^0\overline{r_i} = d_i \cdot {}_{i-1}^{0}R \cdot \overline{z} + a_i \cdot {}_{i}^{0}R \cdot \overline{x}, \quad (8)$$

where $^0\overline{r_i}$ represents the column matrixes form of $\overline{r_i}$ defined in $\{0\}$ referential.

Thus equation (7) can be written in the following form,

$$\begin{aligned} & d_1 \cdot \overline{z} + a_1 \cdot {}_1^0R \cdot \overline{x} + d_2 \cdot {}_1^0R \cdot \overline{z} + a_2 \cdot {}_2^0R \cdot \overline{x} + \ldots \\ & \ldots + d_n \cdot {}_{n-1}^{0}R \cdot \overline{z} + a_n \cdot {}_n^0R \cdot \overline{x} = \overline{0} \end{aligned}, \quad (9)$$

The loop closure equations written above are two fundamental matrix equations by which the general displacement equation of any spatial linkage is obtained. According to equation (7), the next equation can be written for our mechanism

$$\begin{aligned} & l_4' \cdot \overline{z} + l_1 \cdot {}_1^0R \cdot \overline{x} + l_2 \cdot {}_{2'}^{0}R \cdot \overline{x} + l_4 \cdot {}_3^0R \cdot \overline{z} + l_4' \cdot {}_4^0R \cdot \overline{x} - \\ & - a \cdot {}_4^0R \cdot \overline{z} - l_2 \cdot {}_5^0R \cdot \overline{x} = \overline{0} \end{aligned}, \quad (10)$$

Considering equation (6), next equations are obtained,

$${}_1^0R = \begin{bmatrix} \sin\theta_1 & \cos\theta_1 & 0 \\ -\cos\theta_1 & \sin\theta_1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad (11)$$

$${}_{2'}^{0}R = \begin{bmatrix} \cos(\theta_1+\theta_2)\cos\theta_2' & \sin(\theta_1+\theta_2) & -\cos(\theta_1+\theta_2)\sin\theta_2' \\ \sin(\theta_1+\theta_2)\cos\theta_2' & -\cos(\theta_1+\theta_2) & -\sin(\theta_1+\theta_2)\sin\theta_2' \\ -\sin\theta_2' & 0 & -\cos\theta_2' \end{bmatrix}, \quad (12)$$

$$\begin{aligned} {}_3^0R &= \left({}_5^3R\right)^{-1} = \left({}_4^3R \cdot {}_5^4R\right)^{-1} = \\ &= \begin{bmatrix} \cos\left(\theta_3+\theta_4'\right) & -\sin\left(\theta_3+\theta_4'\right) & 0 \\ 0 & 0 & -1 \\ \sin\left(\theta_3+\theta_4'\right) & \cos\left(\theta_3+\theta_4'\right) & 0 \end{bmatrix}, \end{aligned} \quad (13)$$

$${}_4^0R = {}_5^4R^{-1} = \begin{bmatrix} \sin\theta_4' & \cos\theta_4' & 0 \\ 0 & 0 & -1 \\ -\cos\theta_4' & \sin\theta_4' & 0 \end{bmatrix}, \quad (14)$$

$${}_5^0R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (15)$$

Substituting from (11)-(15) into equation (10), we get:

$$\begin{aligned} & l_4' \cdot \overline{z} + l_1 \cdot \sin\theta_1 \cdot \overline{x} - l_1 \cdot \cos\theta_1 \cdot \overline{y} + l_2 \cdot \cos(\theta_1+\theta_2) \cdot \cos\theta_2' \cdot \overline{x} + \\ & + l_2 \cdot \sin(\theta_1+\theta_2) \cdot \cos\theta_2' \cdot \overline{y} - l_2 \cdot \sin\theta_2' \cdot \overline{z} - l_4 \cdot \overline{y} + l_4' \cdot \sin\theta_4' \cdot \overline{x} - \\ & - l_4' \cdot \cos\theta_4' \cdot \overline{z} + a \cdot \overline{y} - l_2 \cdot \overline{x} = \overline{0} \end{aligned} \quad (16)$$

This results in the following equations,

$$\begin{cases} l_1 \cdot \sin\theta_1 + l_2 \cdot \cos(\theta_1+\theta_2) \cdot \cos\theta_2' + l_4' \cdot \sin\theta_4' - l_2 = 0 \\ -l_1 \cdot \cos\theta_1 + l_2 \cdot \sin(\theta_1+\theta_2) \cdot \cos\theta_2' - l_4 + a = 0 \\ l_4' - l_2 \cdot \sin\theta_2' - l_4' \cdot \cos\theta_4' = 0 \end{cases}. \quad (17)$$

From this equations we obtain the inverse kinematics solution, $\theta_1 = f(\theta_4)$ for the flexion-dorsiflexion movement.

### 4. Conclusion

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. Some structural and kinematic aspects are presented in this paper. It's 3D design, some simulations, control aspects and experimental results will be presented in future papers.

### 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.

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