ANKLE REHABILITATION ROBOTIC PLATFORM. PART A: STRUCTURAL SYNTHESIS

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Abstract: The ankle and leg represent an anatomical-functional complex, the role of this complex being to support the body weight in an orthostatic position and to ensure movement, according to the terrain. Therefore, the leg has a static role as well as a dynamic role of equal importance. Ankle joint traumas have an immediate effect on joint instability, so that there is a mobility limitation or even mobility lose of this joint, the ankle needing rehabilitation therapy. A trend of the last decades, in terms of research in the field of robotics, is that of the field of rehabilitation, which aims to improve the rehabilitation process, from the primitive mechanisms currently used, to higher technologies. This trend occurs as a result of the growing number of the aging population, which requires assistance after the occurrence of various accidents. In this paper, structural synthesis of an ankle rehabilitation platform is presented.
Keywords: rehabilitation robot, ankle rehabilitation, structural synthesis.

1. Introduction

Medical robotics represents one of the most promising areas of robotics application. The integration of robotic systems in medicine allows the modernization of the equipment and devices and makes the medical process more efficient. Currently, such robotic systems have been implemented in surgical interventions (surgical robots) of extremely high precision and sensitivity or in procedures intended for medical recovery following various ailments (robotic recovery), etc.

The ankle and leg represent an anatomical-functional complex, the role of this complex being to support the body weight in an orthostatic position and to ensure movement, according to the terrain. Therefore, the leg has a static role as well as a dynamic role of equal importance.

At the level of the ankle joint, the following types of trauma can occur: bone fractures; joint contusions, sprains and dislocations; muscle tears or combinations thereof. Injuries to this joint are the most common of all locomotor system trauma locations [1]. Ankle joint traumas have an immediate effect on joint instability, so that there is a limitation or blocking of the mobility of this joint.

A trend of the last decades, in terms of research in the field of robotics, is that of the field of rehabilitation, which aims to improve the rehabilitation process, from the primitive mechanisms currently used, to higher technologies. This trend occurs as a result of the growing number of the aging population, which requires assistance after the occurrence of various accidents.

Traditional rehabilitation therapies use simple devices such as elastic bands and foam rollers. They also require the constant presence of a therapist. Rehabilitation exercises are long-lasting, repetitive and require effort from both the patient and the therapist.

To counteract these disadvantages, high-performance robotic systems can be used for a complete recovery of the joint. However, the implementation of therapy assisted by robotic systems at the level of recuperative institutions is difficult, due to their high costs. Hence, the need to carry out research, in order to develop platforms with low cost, but with high functionality, which allow a complete recovery of the ankle joint, but also the monitoring of the patient's progress.

The diversity of medical systems designed for medical recovery appeared as a consequence of multiple traumas that affect the functionality of the lower limb. Due to the fact that the pathologies that affect the ankle joint are multiple and different, specialized systems have been designed for its recovery. Thus, recovery systems can be classified and customized according to the condition for which they are intended and the type of exercise applied: robotics platforms, orthotic systems, exoskeletons and other devices.

Parallel robotic platforms are the most common in the recovery of the ankle joint, because they have a number of favorable characteristics, such as: low inertia, increased rigidity, high portability.

The parallel robot built by Yoon et al. is a reconfigurable robot that allows a wide range of exercises [2]. The Stewart platform, referred to as the "Rutgers Ankle", is a haptic interface platform developed for use in rehabilitation [3-6]. Starting from Stewart-type platforms, a robotic platform was developed that can provide assistive rehabilitation. The movement of the joint is controlled by changing the lengths of six linear actuators, two mounted behind the heel and four mounted on the sides of the foot. The foot is placed on the support plate, on which a slipper has been previously placed, to facilitate the access of the user. The experimental results suggest that the robotic platform can reproduce both the movement made by the patient during locomotion and the movement made by a therapist during a rehabilitation exercise. The disadvantage of this platform is the actuation method, which presents nonlinearities in the force transmission, as well as the need to use an external source of compressed air [7].

To provide three degrees of freedom (d.o.f.), necessary to perform the range of motion and muscle-strengthening exercises specific to rehabilitation, an ankle joint rehabilitation system has been designed, which contains a fixed, U-shaped base plate that holds the support structure of the calf and a support plate for the foot and ankle [8,9]. Although it is an innovative rehabilitation system, the major problem is the control of the robot's force and position, which is difficult to achieve due to the non-linear character of the pneumatic artificial muscles.

The ARBOT platform is based on a parallel mechanism with two d.o.f. [10]. The mechanical structure of this robotic platform is composed of a fixed base plate, to which a support link is connected by means of an universal joint, a support plate, which constitutes the final link, and three actuators. An actuator is a DC motor that drives a system of pulleys, converting rotational motion into linear motion. A force sensor, mounted between the mobile platform and the leg, is used to determine the degree of interaction between the human and the robot. The exercises can be active or passive, the experimental results demonstrating a high performance of the rehabilitation system.

PKankle is a robotic platform that allows rotations around the instantaneous center of rotation of the ankle [11]. This platform has three d.of. and can measure the forces and moments exerted by the patient's leg during recovery exercises. The estimation of the location of the joint rotational axes was made based on the medical literature in the field. The movement of the final link, the sole support, is optimized using kinematic and dynamic analysis, allowing smooth and comfortable movement for patients.

Another robotic platform with three d.o.f was proposed, which allows patients to perform exercises with only the affected leg, or with both legs at the same time [12]. Three types of exercises are implemented, depending on the patient's degree of recovery. The development proposals suggest the use of a graphical user interface and the integration of exercises into virtual reality models.

A prototype rehabilitation platform was developed by Meng et al., actuated by artificial muscles [13]. Four pneumatic muscle type actuators offer three d.o.f., the compliance at the joint level offering the possibility of adjusting the robot's stiffness in the interaction with patients. The variation of the degree of difficulty of the exercise is achieved with the help of the variation of the pressure in the artificial muscles. There are also robotic platforms operated with the help of only three artificial muscles, such as the one developed by Ai Q. et al. [14].

A low-cost parallel robot for ankle rehabilitation was developed by Vallés et.al. [15]. The system has three prismatic-revolute-spherical kinematic chains, this configuration allowing three d.o.f. The actuators used are brushless servomotors, and the system control is carried out with the help of a PC.

A specialized robotic system for ankle joint recovery was built by Lin et al. [16,17]. A torsion sensor monitors the interaction between the ankle and the robot, and is placed between the sole support plate and the servo motor. Safety measures have been implemented with the help of a control algorithm so that the robot stops if certain predefined limits of speed or amplitude of movement are exceeded. Also for safety, an emergency button has been placed, which the patient can press to stop the robot immediately. The angle made by the ankle joint is presented to the patient, in real time, by means of a display.

PediAnklebot is a rehabilitation system developed at the Massachusetts Institute of Technology, targeting children with motor disabilities between the ages of six and ten [18]. The system allows three d.o.f. of the ankle joint, having the possibility of being used both during rest (in a chair) and during walking.

Among the systems currently on the market, we mention the systems offered by Biodex. This company has a wide range of robotic systems used for medical recovery, among which we list "System 4 Pro", "Balance System SD" and "Unweighing System" [19].

Based on the study of the existing literature, it can be said that the use of robotic systems, as a modern alternative to classical medical recovery, is very useful. Although the current literature notes a multitude of systems used in medical recovery, it can be said that at the moment there is no system that fully satisfies the patient's need for recovery and that does not face some technical problems. Consequently, the conception, development and implementation of rehabilitation platforms, adaptable to the patient's needs, are justified and will be the object of study of this work.

2. Structural Synthesis

The movements allowed by the ankle joint (Fig. 1) provide the basic concepts for the design of the rehabilitation system, determining the configuration of the mechanism. In the designing process, we start from the premise that the rehabilitation system must ensure the dorsiflexion and plantar flexion movements, as well as the eversion and inversion movements, necessary for a complete recovery of the ankle joint. The abduction and adduction movements are not key elements in the recovery of this joint, they representing secondary movements. The angular amplitudes for these movements vary between 25° to 50° degrees for plantar flexion, 20° to 30° for dorsiflexion, 35° to 50° for inversion and 0° to 25° for eversion [20]. So the system must have a spatial kinematic structure that allows rotations around two perpendicular axes, which means that the platform on which the sole of the foot rests must have two d.o.f.

Starting from the basic movements of the ankle joint (Fig. 1), new kinematic solutions of mechanisms two d.o.f. will be proposed, which can constitute the basic kinematic structures of some systems for the rehabilitation of plantar flexion / dorsiflexion and inversion / eversion movements of the ankle joint. Both "fixed" robotic platform versions will be proposed, with the base fixed to the ground, as well as "portable" versions, with the base fixed to the calf. For all these variants of rehabilitation systems, the driven link is the plate on which the sole of the foot whose ankle needs to be rehabilitated is placed. None of the variants of robotic platforms mentioned above can be used while walking, but the "portable" variants can be moved, before, during or after the rehabilitation process, the mechanism base being fixed to the calf. Most rehabilitation systems in this category use parallel mechanisms to reduce the size of the robot. Except for systems based on the Stewart platform, which is capable of providing six d.o.f. to the driven link, the vast majority of other proposed designs provide one or two d.o.f. to this link.

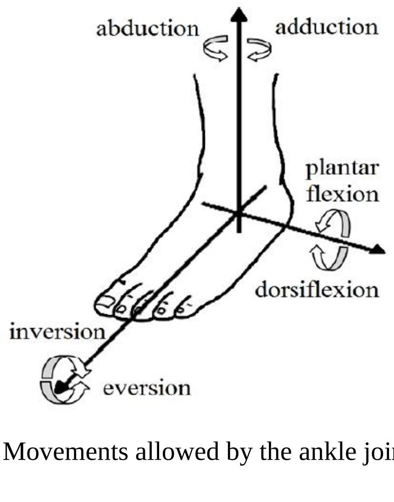


Fig. 1. Movements allowed by the ankle joint [21].

We will consider the driven link of the mechanism of an ankle joint rehabilitation system, link that will support the sole of the foot. In the ideal case, this link should have three d.o.f. (relative to the movements allowed by the ankle joint), which means that it can be connected to the base by means of a spherical joint (Fig. 2).

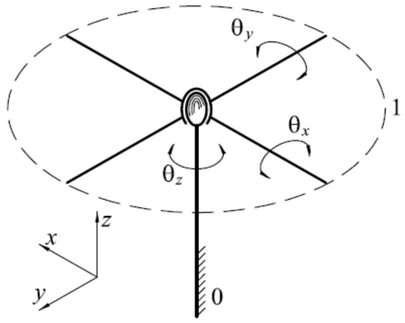


Fig. 2. General principled schematic of a robotic platform with three d.o.f.

There are multiple solutions for actuating the driven link 1. One of these solutions, proposed by the authors, is a very compact one and it is based on a 3-SPS/S (spherical – prismatic – spherical / spherical) mechanism (Fig. 3), with the prismatic joins as driving joints. Since the central support bar (the base) prevents the driven link from having translations along the three axes of a Cartesian frame, this link (the sole support plate) will only be able to perform three rotational movements around the mentioned axes.

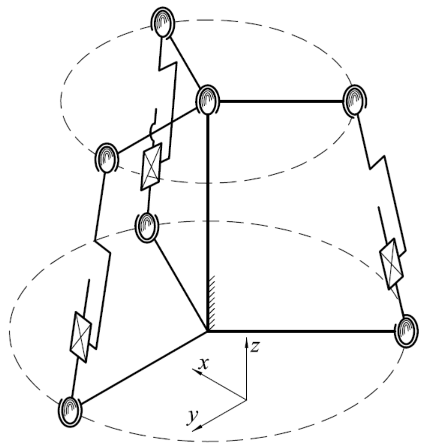


Fig. 3. General kinematics of a 3-SPS/S robotic platform.

A second actuation solution that will be considered by the authors is the one based on a 3-RSS/S (rotational – spherical – spherical / spherical) mechanism (Fig. 4), with the revolute joints as driving joints.

Since the abduction and adduction movements are not key elements in the recovery of this joint, being considered secondary movements, the design of systems that rehabilitate plantar flexion / dorsiflexion and inversion / eversion movements are considered, which means that the driven link (the plate of supporting the sole) will must have two d.o.f. (rotational movements around two perpendicular axes belonging to a horizontal plane, Fig. 5).

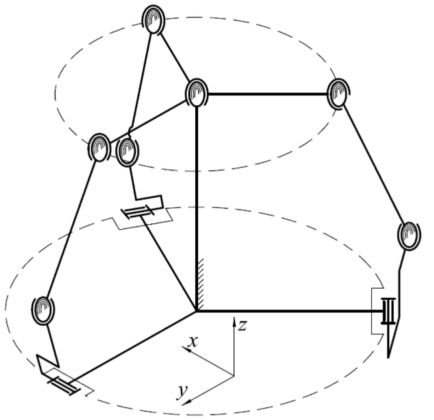


Fig. 4. General kinematics of a 3-RSS/S robotic platform.

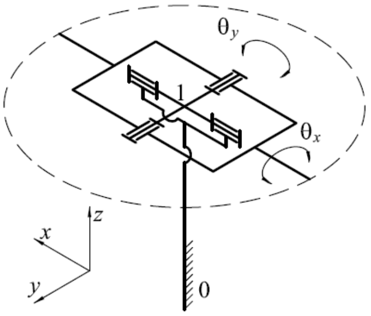
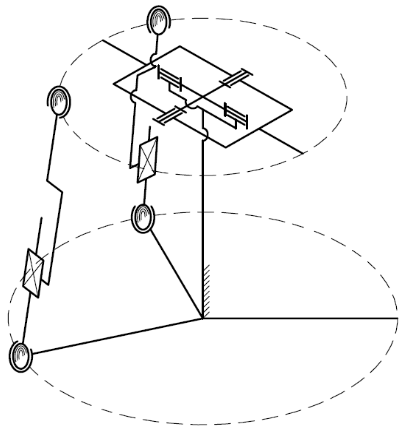


Fig. 5. General principled schematic of a robotic platform with two d.o.f. [22, 23].

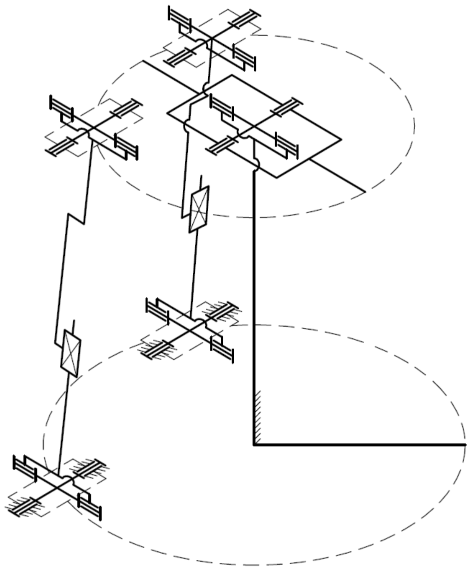
Under these conditions, the first actuation solution of the driven link with two d.o.f. can use a 2-SPS/U (spherical – prismatic – spherical / universal) mechanism, Fig. 6.a. However, in order to avoid the rotation of SPS kinematic chains around their own axes (aspect not allowed for functional reasons), a 2-UPU/U (universal – prismatic – universal / universal) mechanism could be used (Fig. 6.b).

To actuate prismatic joints, linear actuators (pneumatic or hydraulic actuators) or rotary actuators and additional mechanical transmissions must be used, which should convert a rotational motion into a translational one. Pneumatic or hydraulic actuators require an external fluid source (gas or liquid under pressure) that is not typically available at home. In addition, they exhibit nonlinearities in both force and flow dynamics.

Mechanical transmissions such as ball screw or rack and pinion transmission are complicated and expensive. This is why we want to use the advantages of the Scotch-Yoke mechanism (it has a high output torque and smooth operation).



(a)



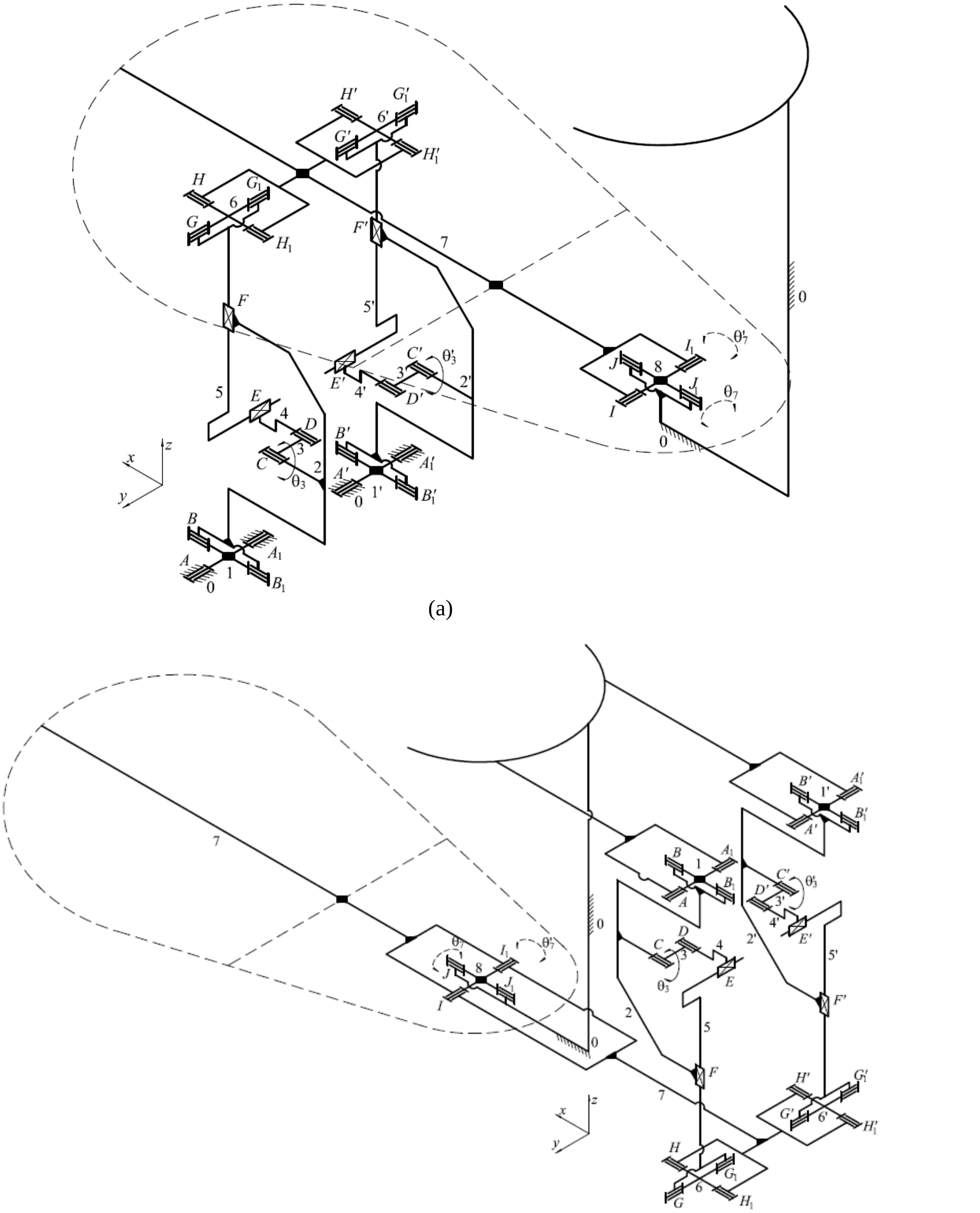
(b)

Fig. 6. Kinematics of a rehabilitation platform with two d.o.f.: a) platform based on a 2-SPS/U mechanism; b) platform based on a 2-UPU/U mechanism.

Two structural variants of the solution based on the translation slide mechanism will be proposed. A first variant (variant SV-1) has a fixed link (link 0, the base) connected to the ground and also to the calf (see Fig. 7.a). This structural variant will be called the "fixed version". The foot will be placed on the driven link 7 and the ankle joint will be forced to be recovered for the two movements mentioned above. The amplitudes of these movements are variable and progressively controlled to avoid ankle injury.

The structural synthesis of the mechanism for the portable version is based on the same comments presented above. This second variant of the first actuation solution (variant SV-2), called the "portable version" (see Fig. 7.b), implies that the sole of the foot is connected to the driven link 7 and the link 0, the base, is connected to the calf. In this case, the leg is suspended (with the leg resting on a solid support, a chair, for example).

For the structural variant SV-1, the fixed link 0 is tied to the ground, being connected, at the same time, to the calf by means of straps. For the SV-2 variant, the fixed link is tied only to the leg, the platform being suspended this time (it does not come into contact with the ground). For both solutions, links 3 and 3' are the driving links, while plate 7 is the driven link.



(a)

(b)

Fig. 7. Kinematics of a robotic platform based on the Scotch-Yoke mechanism: a) fixed version (variant SV-1), [24]; b) portable version (variant SV-1).

The sole of the foot will be placed on link 7 (connected by means of straps to this link), and the ankle joint will be forced to be recovered thanks to the two movements around the x (with the angle θ_7) and y (with the angle $\theta_{7'}$) axes, respectively the inversion / eversion and plantar flexion / dorsiflexion movements. To produce the inversion / eversion movement of the ankle joint, the driven link 7 must be rotated by the angle θ_7 around the x-axis. In this sense, the driving links 3 and 3' will be rotated by the same angle $\theta_3 = \theta_{3'}$, in the same direction. When these driving links are rotated by the same angle but in opposite directions, $\theta_3 = -\theta_{3'}$, the link 7 will be rotated by the angle $\theta_{7'}$ around the y-axis, producing the plantar flexion / dorsiflexion movement.

For the second actuation solution of the driven link two d.o.f. (Fig. 3), a 2-RSS/U (rotational - spherical - spherical / universal) mechanism can be used, Fig. 8.a. For the previously mentioned reasons, it is proposed to use a 2-RSU/U (rotational - spherical - universal / universal) type mechanism (Fig. 8.b).

Kinematics for the "fixed version" of the rehabilitation system based on the spatial four-bar mechanism (variant SV-3) is presented in Fig. 9, and the "portable version" of this actuation solution (variant SV-4) is represented in Fig. 10.

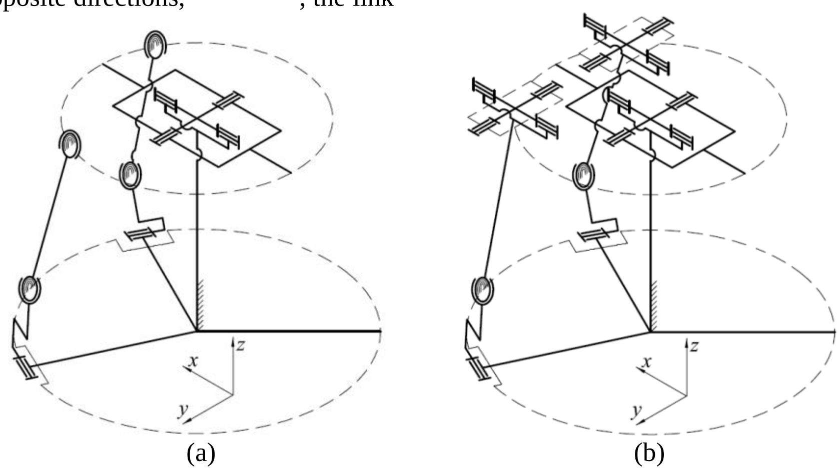


Fig. 8. Kinematics of a rehabilitation platform with two d.o.f.: a) platform based on a 2-RSS/U mechanism; b) platform based on a 2-RSU/U mechanism.

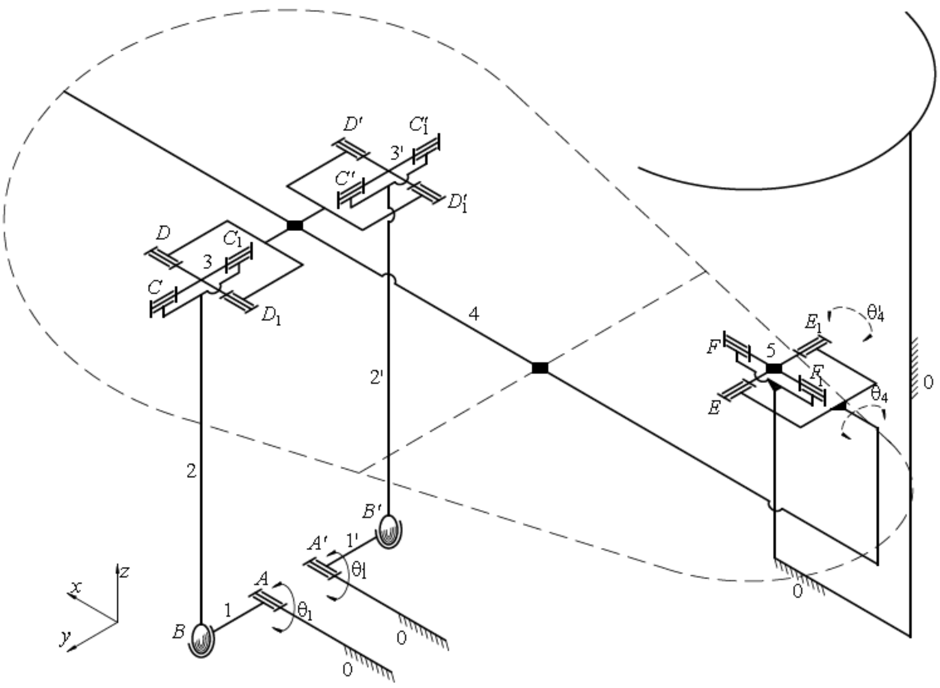


Fig. 9. Kinematics of a robotic platform based on the spatial four-bar mechanism, fixed version (variant SV-3), [23-25].

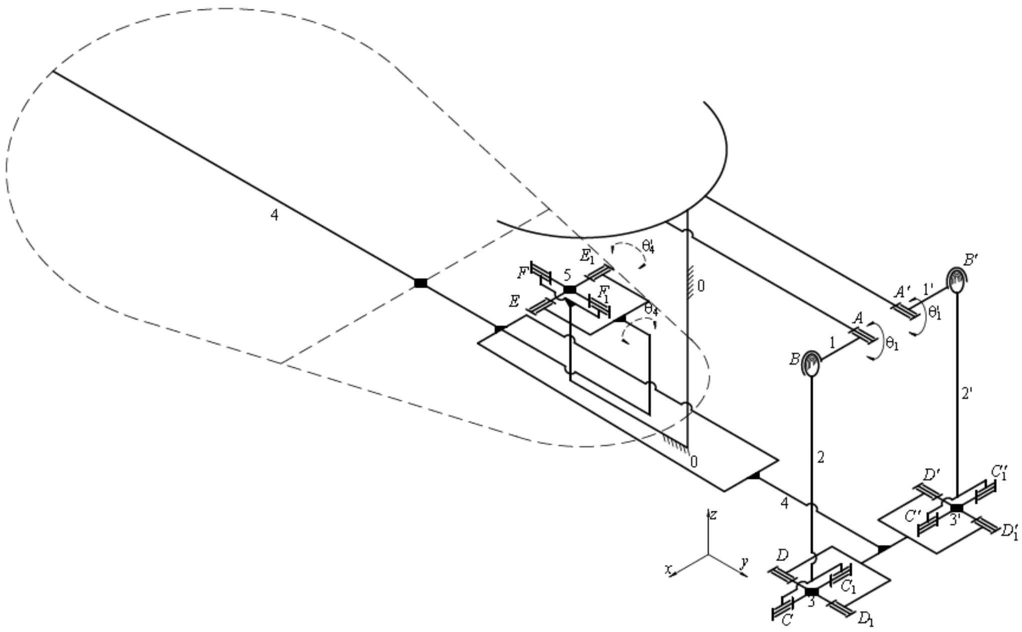


Fig. 10. Kinematics of a robotic platform based on the spatial four-bar mechanism, portable version (variant SV-4), [26].

For the structural variant SV-3, the fixed link 0 is tied to the ground, being connected, at the same time, to the calf by means of straps. For the SV-4 version, the fixed link is tied only to the leg, the platform being suspended this time (it does not come into contact with the ground). For both solutions, links 1 and 1' are the driving links, while plate 4 is the driven link. The sole of the foot will be placed on element 4, and the ankle joint will be forced to be recovered thanks to the two movements around the axes *x* (with the angle θ_4) and *y* (with the angle $\theta_{4'}$), respectively the inversion / eversion and flexion / extension movements. To produce the inversion / eversion movement of the ankle joint, driven link 4 must be rotated by the angle θ_4 around the *x*-axis. In this sense, the driving links 1 and 1' will be rotated by the same angle $\theta_1 = \theta_{1'}$, in the same direction. When these driving links are rotated by the same angle but in opposite directions, $\theta_1 = -\theta_{1'}$, the link 4 will be rotated by the angle $\theta_{4'}$ around the *y*-axis, producing the plantar flexion / dorsiflexion movement.

3. Conclusions

Ankle joint traumas have an immediate effect on joint instability, so that there is a mobility limitation or even mobility lose of this joint, the ankle needing rehabilitation therapy.

Traditional rehabilitation therapies use simple devices such as elastic bands and foam rollers. They also require the constant assistance of a therapist. Rehabilitation exercises are long-lasting, repetitive and require effort from both the patient and the therapist.

To counteract these disadvantages, high-performance robotic systems can be used for a complete recovery of the joint. However, the implementation of therapy assisted by robotic systems at the level of recuperative institutions is difficult, due to their high costs.

This led to the need to carry out research in order to develop new solutions of robotic platforms, with a low cost, but with high functionality, which would allow a complete recovery of the ankle joint, but also the monitoring of the patient's progress.

For this purpose, a structural synthesis was performed, starting from the basic movements allowed in the ankle joint, in order to identify new structural schemes of rehabilitation platforms.

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