Design and Performance of the New Ankle Joint Exoskeleton

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***Abstract*—As one of the most injured joints of the human body, the ankle is often prone to sprains or fractures that require help in movement to restore mobility. While physical therapists typically perform rehabilitation in one-on-one sessions with patients, several successful robotic rehabilitation solutions have been proposed in recent years. However, their design is usually bulky and requires the patient to sit or stand in a static position. This paper presents devotes to a new design of a device as an exoskeleton for the ankle joint that promotes movement of a person with disability. The proposed design is characterized by a lightweight and inexpensive design for various users with easy-to-wear functions and simple operation. The exoskeleton is supported by four linear electric actuators to enable ankle movements in three directions. A CAD model is developed for proposed design parts and simulations, the results of which provide data on the feasibility of the design and its main performance characteristics. 3D modeling and simulation calculations were performed in a virtual environment using Solidworks Simulation software and motion simulation. Solidworks Simulation provides an electric linear actuator that generates ankle movement. The proposed design of the mechanism using kinematic and static models is analyzed, a scheme of the control structure is developed.**

***Keywords*—medical robots design, exoskeletons, rehabilitation devices, ankle joint exoskeleton**

I. Introduction

The human ankle joint is a very complex bony structure of the human skeleton and plays an important role in maintaining the balance of the body when walking [1]. However, little is known about the impact of robotic therapy on ankle recovery after injury and the most effective intervention in a particular case.

Sprains of the ankle joint are very common and can occur even when walking, which leads to significant pain and inflammation [1]. Without rehabilitation, sprains of the ankle joint can lead to chronic pain [2].

Physiotherapy is one of the health sciences dedicated to the treatment of injuries, such as sprains of the ankle joint, with the help of therapeutic exercises [3]. Physiotherapy, including rehabilitation, helps to restore lost functions [2-3].

Recently, there has been an increased interest in studying the effectiveness of therapy, which helps patients recover faster after ankle sprain [4]. In most cases, the treatment of sprains of the ankle joint begins from the first day of injury and continues until painless walking is restored. The recovery period depends on the degree of ankle sprain and usually takes from two to eight weeks to restore full mobility [5]. Compliance with the rehabilitation plan under the guidance of a therapist at least three times a week will reduce complications of ankle sprain [6].

The purpose of rehabilitation exercises is to perform certain movements that cause the patient to have motor plasticity and, consequently, improve motor recovery and minimize functional deficiency.

Rehabilitation of movement depends on the limb, so the affected limb must be trained [4].

Rehabilitation therapy is very important for recovery, and therefore a lot of research is being done in this area.

The rehabilitation process aimed at restoring significant mobility can be divided into three stages [4–6]:

- A bedridden patient is transferred to a chair as soon as possible.
- Walk recovery.
- Walk improvement. (i.e., learning to walk freely, if possible).

Traditional rehabilitation therapy is very time-consuming, especially for recovery, it often requires more than three therapists together to manually help the patient's legs and torso to perform the exercises.

In general, robots for ankle joint rehabilitation can be divided into two categories: robotic orthoses (or exoskeletons) and platform robots. A patient's ankle can

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be led to movement by robotic orthoses, creating additional strength [7].

Platform robots are usually used in a sitting position—a mobile platform transmits efforts and performs rehabilitation movements of the ankle joint [8–9–10]. For example, Jamwal *et al.* (Fig. 1A) has developed an ankle rehabilitation robot for the treatment of ankle injuries through physical load [11]. Zhang *et al*. (Fig. 1B) proposed an adaptive trajectory tracking management strategy implemented on a parallel ankle rehabilitation robot with force distribution in the articular space [12]. Chang and Zhang (Fig. 1C) made research of a parallel mechanism of the ankle joint rehabilitation with three freedom degrees of rotation and the function of movement separation [13]. Ai *et al.* (Fig. 1D) presented a robot for the ankle joint rehabilitation with two freedom degrees put into action by pneumatic muscles [14]. Ayas and Altas (Fig. 1E) have developed an adaptive access control scheme based on fuzzy logic for a parallel ankle regaining robot [15]. Abu-Dakka *et al.* (Fig. 1F) designed a 3-PRS robot for ankle joint rehabilitation based on a learning management system [16]. Zuo *et al*. (Fig. 1G) examined a wearable parallel robot for the ankle joint rehabilitation [17]. M. Russo and M. Ceccarelli (Fig. 1H) developed a lightweight wearable device to support ankle movement (CABLEankle). CABLEankle was based on a parallel S-4SPS construction managed by a cable, which helps when moving [18].

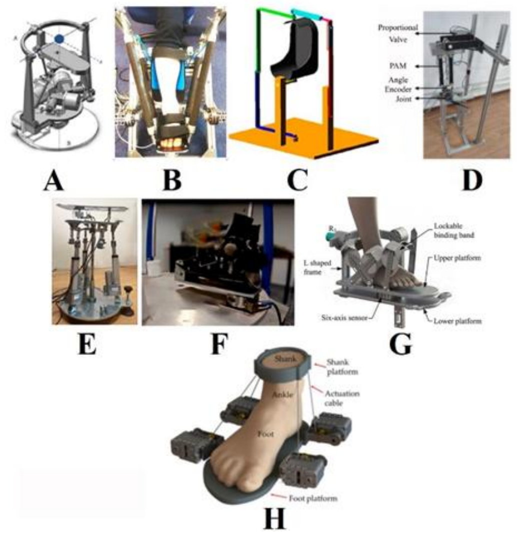

Figure 1. A) Jamwal et al. B) Zhang et al. C) Chang and Zhang D) Ai et al. E) Ayas and Altas F) Abu-Dakka et al. G) Zuo et al. H) M. Russo and M. Ceccarelli (CABLEankle)

As mentioned above, there is a lot of literature on the development of robots for ankle rehabilitation, which can replace the physical efforts of therapy and the performance of physical movements without the guidance and assistance of a therapist [19].

This article proposes the design and development of an exoskeleton for the ankle joint rehabilitation. The main purpose of this study is to achieve performance of the most important rehabilitation movements of the ankle joint (dorsiflexion/plantarflexion, abduction/adduction, inversion/eversion.) using a reliable mechanism and a simple controller. Another aim of the research is to provide a starting point for further study using a 3DOF ankle rehabilitation robot demonstrating practical developments in real-world rehabilitation applications.

The innovation of the study is the use of the electric linear actuators in an ankle exoskeleton with 3 DOF. Thus, the device allows improving the field of rehabilitation with new ways of management.

II. Materials and Methods

This section describes the design process of the proposed ankle rehabilitation device with the main methods used for the synthesis and analysis of the mechanism. Firstly, the requirements for movement are determined by studying the biomechanics of the human ankle joint with an emphasis on its mobility. Then a conceptual design of the mechanism with its main characteristics is introduced.

III. Ankle Anatomy and Motion Requirements

To obtain the technical characteristics of a robot for the rehabilitation of the ankle joint—or the primary design specifications—the anatomical data of the human ankle joint were considered [20].

The ankle joint can perform three different movements:

(a) dorsiflexion/plantarflexion.
(b) abduction/adduction.
(c) inversion/eversion.

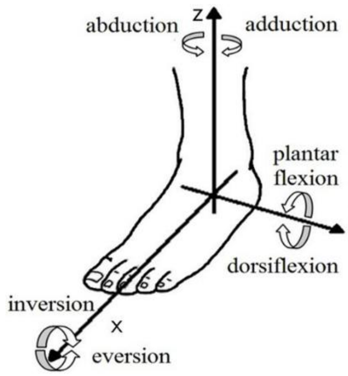

Figure 2. Movements in the ankle joint in three orthogonal planes

The ankle is a hinge-type synovial joint and is involved in lower limb stability. The ankle and foot contain 26 bones connected by 33 joints, and more than 100 muscles, tendons, and ligaments [21].

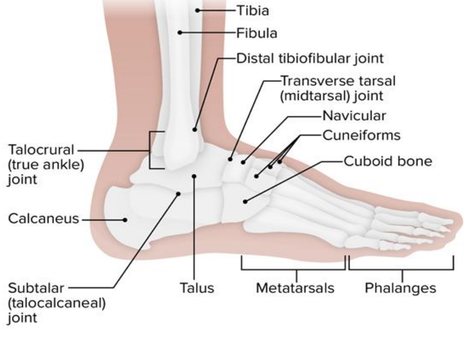

Figure 3. Medial ligaments of the tibiotalar joint.

The ankle joint is located between the lower ends of the tibia and fibula and the upper part of the tarsal bone. This joint is supported by ligaments such as the medial or deltoid and lateral ligaments (anterior talofibular, posterior talofibular and heel ligaments). The foot plays an important role in maintaining body weight and in movement. It can be divided into three parts - the posterior, middle and anterior foot - formed by the following bones: ram, heel, navicular, cuboid, and cuneiform, metatarsal and phalanges. The ankle joint consists mainly of two joints: the talocrural joint and the talocalcaneal joint. However, in biomechanical modeling, it is usually considered as a single joint. There are two movements that occur around the transverse axis between the malleoli:

- Dorsal flexion (or dorsiflexion). This movement brings the foot dorsally to the anterior surface of the leg. The range of motion in this movement is up to 20°. The muscles involved in dorsiflexion are the tibialis anterior, extensor hallucis longus, extensor digitorum longus and fibularis tertius.
- Plantar flexion. This is the opposite movement to dorsiflexion. It occurs, for instance, when the toes are in contact with the ground and the heel is raised off the ground. The range of motion in plantar flexion is from 40° to 50°. Plantar flexion involves the gastrocnemius, soleus, and plantar muscles.

The foot is a complex multi-joint structure that plays an important role in walking and stability when standing. The joints of the foot that play a role in stability are the tarsal joints: the subtalar joint and the transverse tarsal joint.

In the subtalar joint there is relative motion between the talus and the calcaneus at three different sites. The axis of the subtalar joint lies at approximately 42° in the sagittal plane and at approximately 16° in the horizontal plane [22–23]. This joint enables the following movements:

- Inversion (heel and forefoot). This involves moving the heel and forefoot towards the mid-line, bringing the foot sole towards the median plane. The range of motion for inversion is between 30° and 35°. The muscles involved in inversion are the posterior and anterior tibialis muscles.
- Eversion (heel and forefoot). This consists of moving the heel and forefoot laterally placing the sole of the foot away from the median plane with a range of motion between 15° and 20°. The muscles involved in eversion are the fibularis longus and fibularis brevis.

The transverse tarsal joint is a combination of three separate articular spaces between the calcaneus, cuboid, and talus bones. The movements that this allows are:

- Pronation. This is a combination of forefoot inversion and abduction; the muscle involved is the fibularis longus.
- Supination. This is a combination of forefoot inversion and adduction, with action by the tibialis muscles (anterior and posterior) [24–25].

IV. Development of Ankle Exoskeleton

The main purpose of this work is to present a device that can meet the minimum requirements for physical therapy. The design offers a new solution aimed at implementing linear electric drive at the level of the ankle of the foot using a low-cost one-legged mechanism. The corresponding linear electric drive profile is designed for proper movement during physiotherapy.

The advantage of such a device design is the expected low weight and the corresponding volume of the device body. The device should be light, compact, comfortable to wear and active movements. The most important thing is that the device helps the user to make movements. The device must provide sufficient torque and act quickly to maintain at least the minimum range of required movements.

The body of the PLA exoskeleton is a very popular material for 3D printing. It's not perfect for all options because it's impossible, but it's still very versatile. PLA stands for polylactic acid (or polylactide). This conventional thermoplastic is easy to print, biodegradable and inexpensive. It is mainly used for rapid prototyping, creating demonstration models, or for educational purposes.

The most important thing is that the device helps the user to make movements. The device must provide sufficient torque and act quickly to maintain at least the minimum range of required movements.

The design was based on a full range of movements for ankle rehabilitation.

The ranges of movement of these modes are characterized by significant variability in different people due to geographical cultural differences, anatomical structures, and different data collection methods.

TABLE I. Ranges of Motion of the Human Ankle Joint, Fig 2

Motion	Dorsiflexion (deg)	Plantarflexion (deg)	Abduction / Adduction (deg)	Inversion /Eversion (deg)
Range limits	20	50	±10	±12

The corresponding profile of the linear electric drive is designed for correct movement during physiotherapy.

The design of the mechanism in Fig. 4 works with four linear electric actuators that are installed parallel to the spherical joints between the lower leg and ankle joint, respectively. The translational movement of linear electric actuators provides rotation of the ankle and ankle joints.

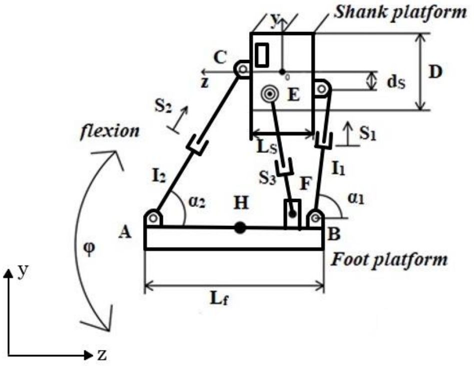

Figure 4. The kinematic design of Ankle Exoskeleton

Such mechanisms contain three drives in each kinematic chain and can make two translational movements and one rotational.

To determine the number of degrees of freedom, we use P. L. Chebyshev's structural formula for a planar mechanism:

$$W = 3 \times (n-1) - 2 \times p_5 - p_4 \quad (1)$$

According to Eq. (1), the number of degrees of freedom of a plane mechanism is:

n – number of links.

p_5 – number of fifth-class couples (single-movement couples);

p_4 – number of pairs of the fourth class (two movable pairs).

According to Eq. (1), the number of freedom degrees of a planar mechanism is:

$$W = 3 \times (8-1) - 2 \times 9 = 3$$

Let's calculate the number of freedom degrees for the planar mechanism in Fig. 4 using the Somov – Malyshev formula:

$$W = 6 \times (n-1) - p_5 - 4 \times p_4 - 3 \times p_3 - 2 \times p_2 - p_1$$

p_i – is the number of kinematic pairs of the –class with $(6-i)$ degrees of mobility ($i = 1, ..., 5$).

The number of degrees of freedom is equal to:

$$W = 6 \times (8-1) - 5 \times 9 = -3$$

Based on the kinematics of the connecting solutions in the design of the exoskeleton in Fig. 4, the angles of articulation of the joints can be expressed as follows:

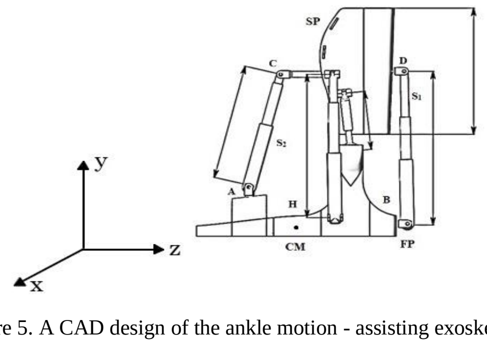

Figure 5. A CAD design of the ankle motion - assisting exoskeleton

The relative movement of the platform attached to the foot relative to the platform attached to the calf can be expressed as ${}^{AB}R = R_z(\alpha)R_y(\varphi)R_x(\theta)$, where φ is dorsiflexion/plantarflexion, θ is inversion/eversion, and α is abduction/adduction. When considering relative motion, attention should be paid to the following three points: (a) all drives are always energized, (b) the attachment points of the drives to the platform act as spherical hinges, and (c) the drives are considered as prismatic hinges with a slight axial deformation. The points on which the drives on the platform attached to the ankle can be generically labeled $A_{a_i} = (a_{ix}a_{iy}a_{iz})^T$, and the points on the platform attached to the foot can be labeled $B_{a_i} = (b_{ix}b_{iy}b)^T$. Using the model in Fig. 3, the vector equation of the node closure for each drive can be written as follows.

$$A_{l_i} = {}^{AB}R^{B}b_i - {}^{A}a_i \quad (2)$$

Rehabilitation exercises require performing uniform, slow and controlled movements so that the patient feels the least stress or pain. Since these exercises are performed at a limited speed, the inertial effects and dynamics of movement can be ignored in the analysis. Thus, static analysis can be used to evaluate the effectiveness of the robot.

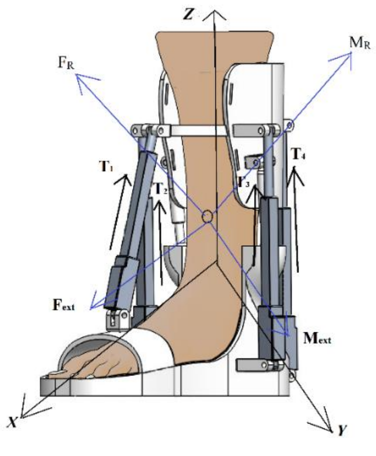

Figure 6. Static model of Ankle Exoskeleton

The voltage in each drive is defined as $T_i = -T_i p_i$ as the product of the unit vector and its intensity, and the vector T here $(T_1 T_2 T_3 T_4)^T$.

$$P^T \cdot T - F_R = F_{ext} \quad (3)$$

and

$$Q^T \cdot T - M_R = M_{ext} \quad (4)$$

where $P^T = [p_1 p_2 p_3 p_4]$ and $Q^T = [b_1 \times p_1 \dots b_4 \times p_4]$.

As mentioned above, since the kinematic representation of the ankle joint is considered spherical, as well as the rotational movement is not limited in the range of motion of the ankle joint, the reaction moment M_R is a zero vector. For the same reason, the full equilibrium equation can be written:

$$\begin{bmatrix} P^T & -I_3 \\ Q^T & 0_3 \end{bmatrix} \begin{pmatrix} T \\ F_R \end{pmatrix} = \begin{pmatrix} F_{ext} \\ M_{ext} \end{pmatrix} \tag{5}$$

The problem with robot operation can be described by solving torque as a function of the movement of the ankle joint.

TABLE II. DESIGN AND OPERATION PARAMETERS OF A CAD SOLUTION IN FIG 5

Size	SP (mm)	FP (mm)	L_1 (mm)	L_2 (mm)	L_3 (mm)	L_4 (mm)
	200	265	243	226	181	93

The passive exoskeleton of the ankle joint consists of fasteners between the foot *(A)* and the shin *(B)* using a ball joint element *(L4)*, and the fastening of the human foot consists of two parts connected to each other by means of loops and attached to the upper part in front *(L1)*, *(L3)* an electric linear actuator attached to the rear and on the front of the ankle. Connections *E* and *F* of the support link the ball joint is the guide link between the shank and the foot platform. The electric linear actuator consists of a system that synchronizes the movement of two interconnected skeletons and moves the ankle together with the exoskeleton.

V. PERFORMANCE CHARACTERISTICS SIMULATION

3D modeling and simulation calculations were performed in a virtual environment using the Solidworks Simulation software and the Motion Simulation add-on.

With the help of the Solidworks simulation, an electric linear actuator is introduced that generates the movement of the ankle joint. Fig. 6 shows the dorsal flexion/plantar flexion obtained using the Solidworks simulation. Dorsal flexion the range of motion in this movement will be up to 20 °, while the imitation will bend up to 15 °. The range of motion in plantar flexion is from 40 ° to 50 °, and in simulation flexion is up to 20 degrees.

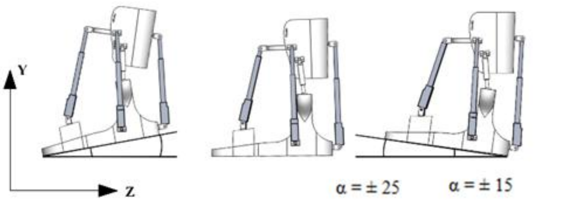

Figure 7. A snapshot of simulated dorsiflexion – plantarflexion assisted motion

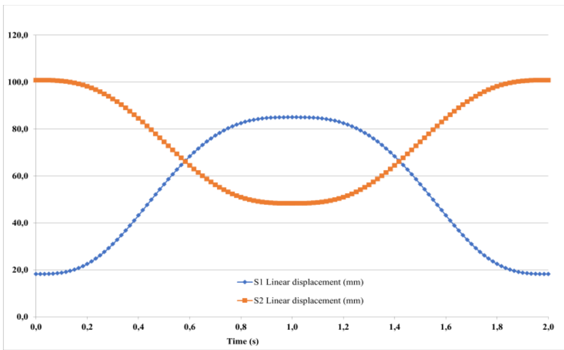

Figure 8. Input data for the simulated motion in Fig. 6 in terms of displacement of linear actuators

Fig. 8 shows components of linear displacement of the platform. From the plot, the motions from all directions are with peaks of maximum values 100 deg/s2. represented for X – component and less than 85 deg/s2 for another components.

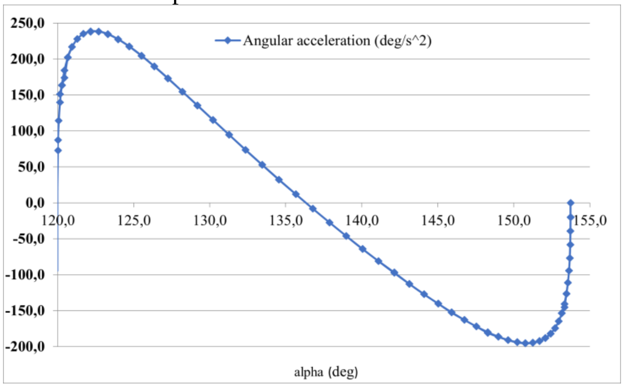

Figure 9. Computed results of the simulated motion in Fig.6 in terms of α angle of the foot platform

The angular acceleration regarding the angle is shown in Fig. 9. The largest value of the acceleration, which equals to 240 deg/s2, is near the top position, and another peak, which equals 150 deg/s2, is near the bottom position.

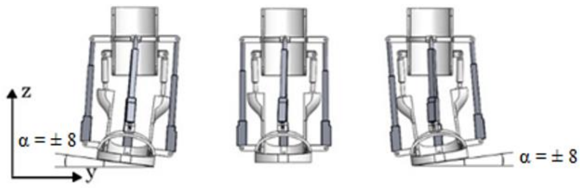

Figure 10. A snapshot of simulated Abduction – Adduction assisted motion

Fig. 11 shows components of linear displacement of the platform. From the plot, the motions from all directions are with peaks of maximum values 30 deg/s^2. represented for Y – component and less than 25 deg/s^2 for another components.

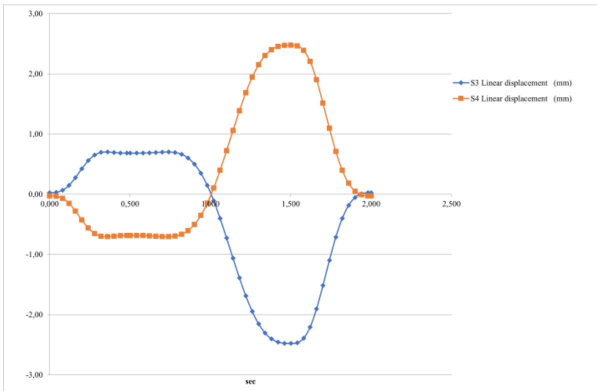

Figure 11. Computed the simulated motion in Fig. 8 in terms of displacement of linear actuators

The angular acceleration regarding the angle is shown in Fig. 12. The largest value of the acceleration, which equals to 230 deg/s^2, is near the top position.

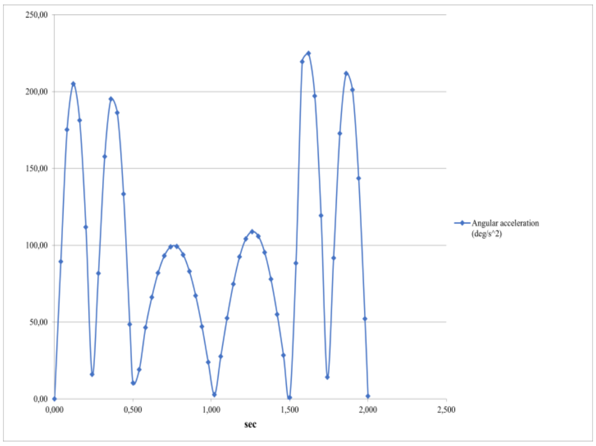

Figure 12. Computed results of the simulated motion in Fig.8 in terms of angle of the foot platform

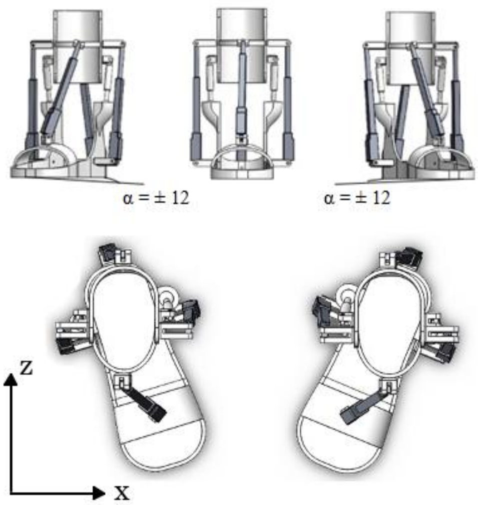

Figure 13. A snapshot of simulated Inversion – Eversion assisted motion

Angular movements are produced by changing the angle between the bones of a joint.

The angular movement is shown in Fig. 14 with 2 seconds 45 Newton seconds. Angular movement characterize the intensity of changes in the modulus and direction of angular velocity during the movement of the ankle joint using an exoskeleton.

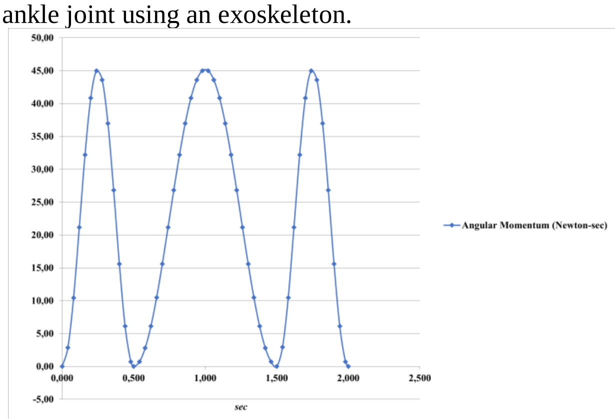

Figure 14. Computed the simulated motion in Fig. 11 in terms of angular movement

The Euler angles shown Fig. 15 describe a sequential combination of passive rotations around the axes of a rotating coordinate system.

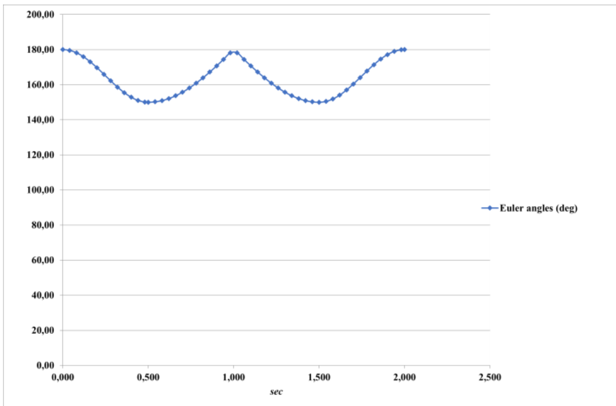

Figure 15. Input data for the simulated motion in Fig. 11 in terms of Euler coal

VI. Structure of Control System

The robot control system, controlled by a linear electric drive, consists of the position of the platform and power control units that descend into it. Such a control system, in turn, allows you to create the necessary torque of the robot's motion drives. Such a robot control system is implemented based on the flowchart shown in Fig. 16. This flowchart is specially designed to treat the patient with two identical active and passive wellness exercises.

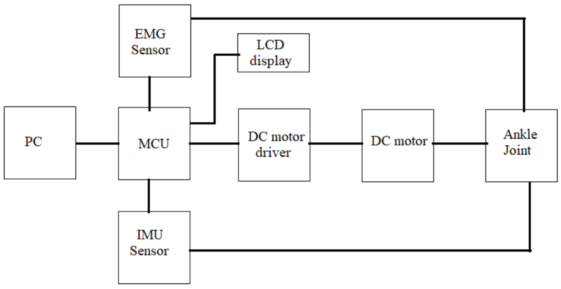

Figure 16. Structure of control system

The sensors in the block diagram in Fig. 16 can be divided into two categories. These are control and control sensors. Sensors such as DC motor driver, EMG sensor, IMU sensor, drive length and voltage sensors are part of the control sensors. They allow you to obtain information such as the angular position/speed, the position of the platform, the length of the drive measured in real time, and, accordingly, the voltage values in the drives, which ensure the constant fulfillment of the «force» equation. The rest of the sensor group includes force sensors. They allow you to measure the force exerted by the patient on the leg and determine the direction in which the patient wants to turn the platform. This allows you to monitor the patient's reaction and safety. Active physical exercise can lead to increased pressure, which can be a good or dangerous signal after an ankle injury (for example, in people with leg swelling after an ankle injury, these sensors are used to prevent blood pressure from rising to dangerous levels. In addition, these sensors are only used during active training. Because with passive exercises, the pressure does not rise above average.

VII. Discussion

In this chapter, we explore how our results answer the questions we sought to answer at the beginning of our evaluation of the effectiveness of the ankle exoskeleton. The performance of the ankle exoskeleton depends on the speed of the electric linear actuator. If the drive speed value is small, the adaptation will be slow due to large tracking errors and huge transients.

The results in Figs. 11-12 demonstrate that the proposed ankle exoskeleton design can operate in the full range of ankle joint movements without reaching the limits of the joint or device. The values of the actuator tension calculated using the proposed static analysis for the simulated driving modes in Fig. 14 have a maximum value of 45 N. Thus, they are safely within the maximum value allowed by the rotary motor driving the drive. When simulating movement, the load reaches a maximum of 60 N, which is quite stable with a healthy ankle joint, but can be dangerous in the case of rehabilitation of the injured. In the case of rehabilitation exercises, the inversion/eversion and abduction/adduction movements should be limited to a range of less than 10 degrees with a suitable ankle load of less than 30 N. With such a practical range of auxiliary movements, it is convenient to reduce the tension of the actuators to much less than the calculated maximum of 45 N.

The low power consumption of the prototype means that the proposed device can be powered by portable batteries.

VIII. Conclusion

To help restore the patient's ability to move, the proposed exoskeleton is designed for outdoor use for lower body movement, as well as for lifting the weight of an injured person. The proposed ankle exoskeleton is made using inexpensive lightweight components to facilitate movement. The prototype with three degrees of freedom of rotation around a virtual stationary center is designed for intensive and repetitive exercises to restore the legs. Each joint is equipped with a motor and a special construction consisting of a four-position mechanism for linear drive and wrist joints.

This increases the speed and efficiency of the model, the results of which are discussed in terms of operational characteristics. The prototype has been assembled to test the new design, and future work will give a practical description.

The control scheme proposed in this paper considers only the length and speed of the drive. However, improving the overall design scheme in the future may include the use of IMU, force sensors, and EMG sensors to create a controller. Usually, EMG sensors are used only for monitoring, but it would be interesting to use them together with a feedback system to receive motor control commands based on myoelectric signals and transmit them to the PID regulator, so that the rehabilitation robot could better respond to the patient's actions during rehabilitation therapy and contribute to achieve the best result. In general, the management system presented in this paper can combine previously used hardware with new software features and provide management that allows you evaluating and applying the necessary forces and moments at various stages of ankle joint recovery. In particular, the proposed controller helps users to perform both passive and active exercises, keeping the load on the Joint under control. The effectiveness of the proposed system was evaluated only by simulation, soon it is planned to carry out further work in the following areas: preparation of robot prototypes based on the proposed control system and testing of the obtained prototypes in experimental conditions on both healthy people and people with limited joint mobility.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Authors Contributions

The co-authors made the following contribution to the development of the article. Balbayev G. and doctoral student Zhetenbayev N. developed the theoretical foundations. The model of ankle exoskeleton was developed by Shingissov B., and Zhauyt A. compiled a kinematic model and numerical verification of the scheme. According to the Solidworks Motion program doctoral student Zhetenbayev N. calculated the exoskeleton movement.

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