Development of a Device for Post-traumatic Ankle Rehabilitation

Andrey Knyazev[1](✉), Sergey Jatsun[1], Andrey Fedorov[1], and Jamil Safarov[2]

[1] Southwest State University, 94, 50 Let Oktyabrya st., Kursk 305040, Russia
teormeh@inbox.ru
[2] Azerbaijan Technical University, 25, Hüseyn Cavid pr., Baku AZ1073, Azerbaijan

Abstract. This article discusses a device for active-passive mechanotherapy of the ankle joint. The device is based on a controllable mobile platform equipped with force-moment sensors, on which the patient's foot is mounted by means of cuffs, and the platform rotation angles are controlled by linear motion sensors. The platform of the device is designed in such a way that the rotation axis of the platform always coincides with the centre of the ankle joint. For this purpose, a parallel kinematics mechanism is used, which is based on three linear electric drives. The control system of the device provides both active and passive movement of the platform. For realization of the control algorithm of the mobile platform movement, a mathematical model is developed, which allows establishing connections between angular motions of the mobile platform and linear drives of the parallel mechanism. Models of reaction forces of the platform support on the patient's foot during operation of the device are also described. A functional control diagram of the device is presented, and the modes of operation of the device are described.

Keywords: Ankle Mechanotherapy · Force Control Sensors · Mathematical model · Parallel Kinematics Mechanism · Functional Diagram

1 Introduction

Among injuries of lower extremities, the most widespread are those of distal part of lower leg and ankle, which, according to literature data, make up from 12.0 to 20.0% of all fractures of locomotor apparatus. In 12–39.8% of cases unsatisfactory results of treatment are observed, and the long-term disability lasts from 4 to 8 months. One of the most common injuries sustained by humans is damage to the ankle joint in sports, domestic, industrial exercises, and as a result of car accidents. Falling from heights with a landing on the feet, including parachuting, also often results in injuries to the ankle joint (AJ). Statistically, more than half of all lower limb injuries and about 40% of joint injuries are ankle injuries. We also know that 54% of ankle fractures and dislocations occur at a young age, when the ability to work is important. After an injury, there is a long process of treatment and rehabilitation, and after surgery, rehabilitation can be complicated by prolonged stiffness of the joint. In many countries, work is underway to develop devices and devices that allow for the post-traumatic rehabilitation of the

A. Ronzhin et al. (Eds.): ICR 2023, LNAI 14214, pp. 93–102, 2023.
https://doi.org/10.1007/978-3-031-43111-1_9

individual using AJ passive mechanotherapy devices. This approach makes it possible to perform foot movements according to an individual rehabilitation program (IRP) set by the doctor. The FLEX-02, A3 Ankle CPM, Kinetec Breva ankle, and ARTROMOT SP3 are widespread [1–3].

At the same time, due to the influence of indefinitely variable parameters of the AJ muscular system, it is difficult to ensure the required accuracy of the patient's foot movement along the trajectory set by the doctor, which reduces the effectiveness of the rehabilitation process. Therefore, the creation of such devices requires an in-depth study of the theory of human-device interaction, creation of man-machine interfaces, mathematical models, and control algorithms that provide the specified quality indicators. Thus, the issues of developing and creating robotic devices for post-traumatic ankle rehabilitation that provide a given movement of the foot under unpredictable changes in physiological parameters are relevant [4–6].

The aim of the study is to improve the effectiveness of the rehabilitation process with an active-passive mechanotherapy and rehabilitation device that provides a given precision through adaptive control of foot movement, taking into account the individual characteristics of the patient's AJ.

2 Tasks of Ankle Rehabilitation

The main objectives of ankle rehabilitation during the recovery period:

- reverse the processes of muscle atrophy and destructive changes in the vessels;
- return mobility to the joint;
- prevent stagnation of fluids in the reconstructed limb;
- increase the motor activity of the joint.

In the early stages of rehabilitation, it is necessary to perform simple movements of the foot in small ranges at a slow pace. Movements such as plantar flexion and dorsiflexion as well as pronation and supination. The exercises are shown in Fig. 1. Once the rehabilitator has noticed an improvement in the ankle's motor function, the range of motion can be gradually increased.

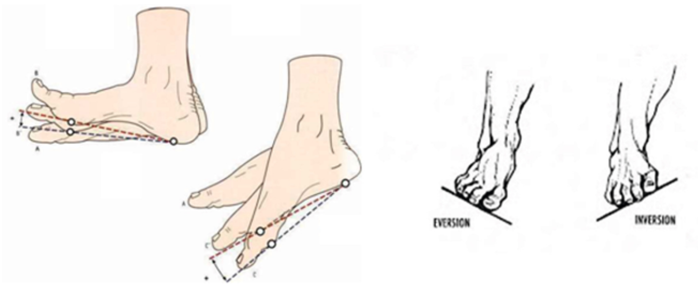

Fig. 1. Exercises for early rehabilitation.

All therapeutic and rehabilitation measures are determined by the severity of the injury as well as the individual characteristics of the patient. After the cast is removed, it is important to put stress on the ankle joint gradually. The exercises are shown in Fig. 2.

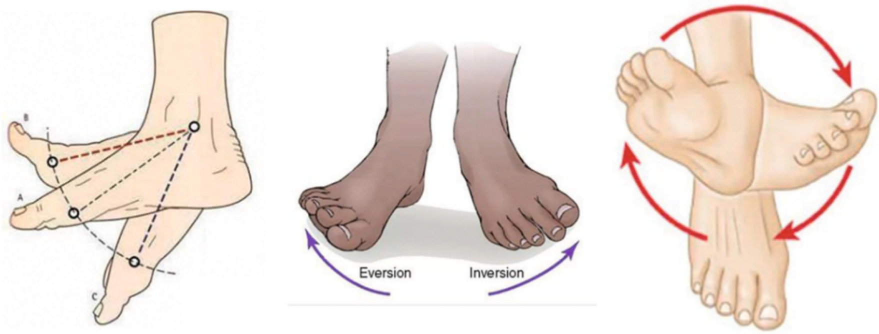

Fig. 2. Exercises for the final stage of rehabilitation.

In the final stage of recovery, you should start gradually combining these two movements by making circular movements with the foot. Also, continue to perform the operations described in the first phase, but with larger rotation angles until the ankle is able to perform the movements within the usual ranges of motion. The normal ranges of motion of the foot are shown in Fig. 3 [7, 8].

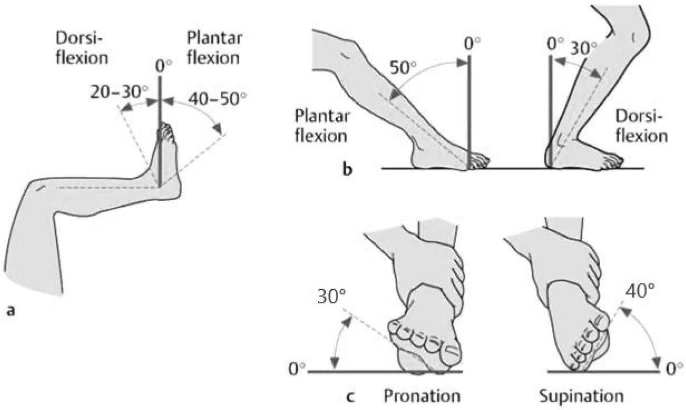

Fig. 3. Range of motion of the healthy ankle.

3 The Circuit Diagram of the Active-Passive Mechanotherapy Device

The circuit diagram of the active-passive mechanotherapy device for the ankle, shown in Fig. 4, is a parallel manipulator equipped with linear actuators [9].

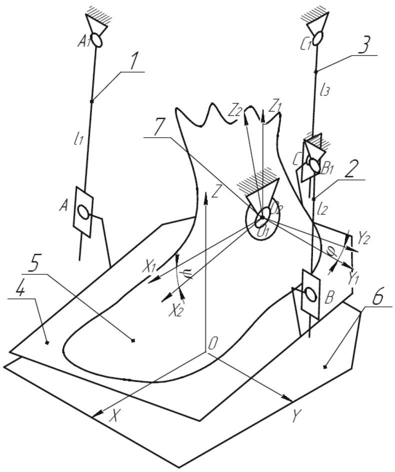

Fig. 4. Spatial kinematic diagram of the appliance.

Figure 4 shows the following designations: 1 is the linear actuator 1 (l_1); 2 is the linear actuator 2 (l_2); 3 is the linear actuator 3 (l_3); 4 is the controlled mobile platform; 5 is the patient's foot; 6 is the platform in initial position; 7 is the virtual joint.

By changing the lengths of the actuators, it is possible to change the position of the controlled mobile platform (CMP) and consequently the patient's foot. The structure of the device includes the patient's foot, mobile platform, electric actuators, power frame sensors, control system. The electric actuators of the manipulator are connected to the body by means of joints A_1, B_1, C_1. Actuators are connected to the platform by means of joints A, B, C. The joints A, B, C, A_1, B_1 are two-coordinate, while C_1 is a single-coordinate joint, capable of changing its position in the sagittal plane [10, 11].

In order for the device to work correctly, the center of rotation of the CMP "virtual joint" O_1, defined by the intersection of the joint axes (A, B, C), must be at the point O_2 of the ankle joint center. During rehabilitation measures, point O_2 remains stationary and all platform movements occur around this point. The radius vectors determining the position of points O_1 and O_2 must be equal $\overline{r}_{o1} = \overline{r}_{o2}$. At the same time, under real-world conditions, there is a tolerance between the vectors, determined by the formula: $\overline{r} = \overline{r}_{o1} - \overline{r}_{o2}$.

We will assume that the trajectories of the mobile platform points satisfying the condition $\frac{|\Delta\overline{r}|}{|\overline{r}_{O_1}|} = \varepsilon \leq 0.01$, are valid trajectories.

A parallel kinematics mechanism (PKM) [12, 13] is used to implement the "virtual hinge" of the platform and ensure the intersection of the mobile platform rotation axes in the center (tibia and talus contact zone) of the AJ, based on three linear actuators.

The ankle joint is formed by the tibia and talus bones. The articular surfaces of the lower leg bones and their ankles are encompassed by the Talus block in a fork-like fashion. The ankle joint is block-shaped. In this joint, flexion (movement towards the plantar surface of the foot) and extension (movement towards the rear surface of the foot) are possible around the transverse axis that runs through the talus block. The subtalar joint is responsible for pronation (rotation of the foot with the sole turning outwards) and supination (rotation of the foot with the sole turning inwards) of the foot. The human foot moves in three planes, the rotation around the vertical axis is caused by the rotation of the lower leg, therefore when working with active-passive mechanotherapy for ankle joint device (APMAJ) you should take this fact into account and not to fix the lower leg, otherwise you can get new injuries.

4 Diagrams for Measuring Leg and Platform Interaction Forces

The principle of operation of the force meter is based on monitoring the relative movement of the upper and lower module elements of the mobile platform at four points. The device has sensors that measure the force between the patient's foot and the mobile platform at these points. In active mode the patient provides the foot movement and the APMAJ platform replicates this movement. Impedance control is used for this. The mobile platform is attached to the patient's foot via a system of elastic connections, the drive platform is equipped with angle sensors and electrically controlled actuators and ensures a defined movement of the foot. When a relative movement of one platform with respect to the other occurs, a deformation of the elastic elements of the measuring device occurs, which is registered by the movement sensor [14–16].

During operation of the device, reaction forces from the platform arise between the patient's foot and the platform. To account for these forces, it is necessary to introduce a model to describe the interactions between the foot and the platform [17].

The foot acts on the platform as a distributed load, so replace it with two concentrated forces. Assume that the foot is in contact with the platform by the heel and metatarsal bones, together they form a bony system, which is connected to the plantar side of the foot by muscular tissues. Figure 5 shows a diagram of the interaction of the foot and platform in the sagittal plane. The following symbols are included in the diagram: 1 is ankle joint; 2 is metatarsal bones; 3 is heel bone; 4 is tibia; 5 is platform; 6 is force-moment interaction sensors.

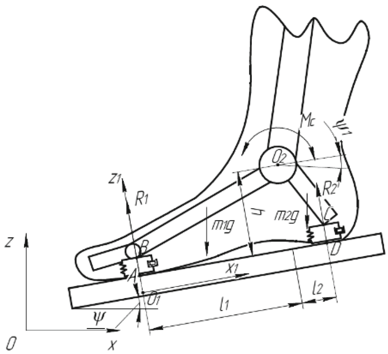

Fig. 5. Diagram of foot and platform interaction in the sagittal plane.

Let's write down the equation of moments for the patient's foot in the sagittal plane:

$$J_{bs}\ddot{\psi} = M_R + M(G) - M_C, \tag{1}$$

where: J_{bs} is the moment of inertia of the bone system;

M_R is the moment created by the support reaction forces;

M(G) is the moment created by the gravity of the bone system;

M_C is the resistance moment of leg muscles.

Let's represent the muscle tissues as a Kelvin-Feugt model, with viscous and elastic components arranged in parallel. Given this, for sagittal plane, we will find forces R_1, R_2 by formulas:

$$R_1 = c_1(\psi - \psi_1) + \mu_1(\dot{\psi} - \dot{\psi}_1), \tag{2}$$

$$R_2 = c_2(\psi - \psi_1) + \mu_2(\dot{\psi} - \dot{\psi}_1), \tag{3}$$

where c is the reduced muscle stiffness coefficient;

μ is the reduced muscle viscosity coefficient;

$(\psi - \psi_1)$ is the relative strain of muscle tissues;

$(\dot{\psi} - \dot{\psi}_1)$ is the relative strain rate of the muscle tissues.

5 Functional Diagram of the Control System

The functional diagram of the APMAJ robotic device is shown in Fig. 6. The diagram consists of a hardware and software system, a physiological parameter monitoring unit, a rehabilitation program selection unit, a signal processing unit, a mobile platform, electric drives, amplifiers, a control unit, a sensor system for measuring linear and angular movements and reactions between the patient's foot and the APMAJ mobile platform in the sagittal and frontal planes [18]. The choice of rehabilitation mode determines the program of movements of the patient's foot, formalized in the form of parametric equations $\overline{\lambda}(t)^* = (\phi(t)^*, \theta(t)^*, \psi(t)^*)^T$. If the conditions are met $\overline{\lambda}(t)^* < \overline{\lambda}(t)_0^*$, where $\overline{\lambda}(t)_0^*$ is the range of permissible rotation angles. The on-board computer (signal processing unit) solves the inverse kinematics task (IKT) and determines the length change laws of the linear actuators $\bar{L}^* = (L_1^*, \mathrm{L}_2^*, \mathrm{L}_3^*)^T$.

Further signals are proportional $\overline{L}^* = (L_1^*, \mathrm{L}_2^*, \mathrm{L}_3^*)^T$ are fed to the appropriate comparison units (comparators), where they are compared with the real values $\overline{L} = (L_1, \mathrm{L}_2, \mathrm{L}_3)^T$. The presence of feedbacks makes it possible to determine the deviation of the real position of the platform from the set position in the form of a vector $\Delta\lambda$ and force interaction vector ΔP. The regulators receive an error value $\Delta\bar{L} = (\Delta L_1, \Delta L_2, \Delta L_3)^T$ for each controlled variable. These values are converted by the control algorithm into control voltages $\overline{U} = (U_1, \mathrm{U}_2, \mathrm{U}_3)^T$.

The force-moment sensing system makes it possible to evaluate changes in the reaction value over time and detect the moment of spastic effects, muscle contractures and automatically change the laws of foot movement in order to eliminate the patient's trauma and pain syndrome. In accordance with the ACS diagram, the actuators are controlled to provide the specified movement of the patient's foot. The feedback channels are the data recorded by the swing angle sensors on the respective axes, as well as the force-momentum sensor values. The LQR-optimization strategy is used to optimize the settings of the controllers to give the required quality performance of the APMAJ control

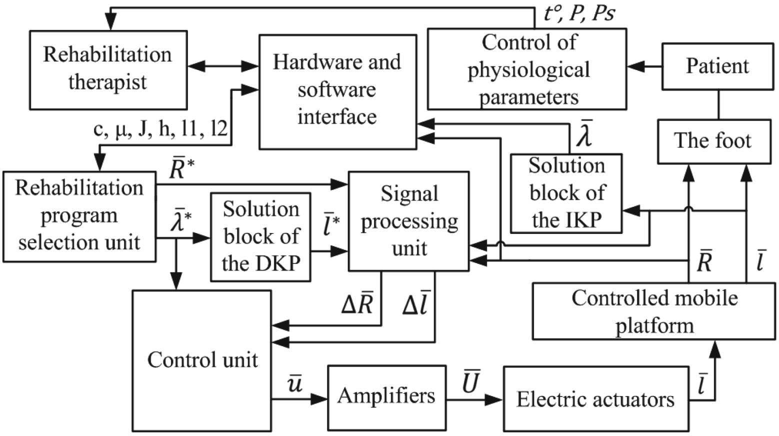

Fig. 6. Functional diagram of the APMAJ robotic appliance.

system. If an abnormal situation occurs (reaction force limits are exceeded), the ACS algorithm allows you to change the exercise pace, perform the complex movements required for safe operation of the device and stop if necessary, thus ensuring safe patient rehabilitation [19].

6 Description of the Unit's Operating Modes

The rehabilitation unit has several modes of operation. Before starting the rehabilitation procedure, the rehabilitation therapist must select the operating mode parameters, using a program on a personal computer. The operation of the device has been simulated in MATLAB/Simulink environment, information about the operation modes is presented below.

Plantar - Dorsiflexion. This robotic mode allows a rotational movement of the patient's foot in the sagittal plane. The range of rotation angle is $42° \leq \psi \leq 23°$. The results of the simulation mode are shown in Fig. 7.

Pronation - supination. This mode of operation allows a rotational movement of the patient's foot in the frontal plane. The range of rotation angle is $40° \leq \varphi \leq 40°$. The results of the simulation are shown in Fig. 8.

Any rehabilitation mode should be set according to the recommendations of the rehabilitation therapist. In this mode, the person's foot can perform both combined and circular movements of the foot. The mode chosen by the user can include changing direction, speed of movement and number of repetitions (Fig. 9).

The effectiveness of rehabilitation interventions depends largely on factors such as gender, age, duration of disability, educational level, and occupational affiliation of the patient. The Barthel and Rankin scales record the condition without offering the patient understandable benchmarks for the dynamics of the rehabilitation process, do not allow for accessible formulation of rehabilitation goals and motivation of the patient. Thus, these scales are appropriate for a screening assessment of the overall rehabilitation process. RMI, HAI and the KX test are recognized as informative techniques that

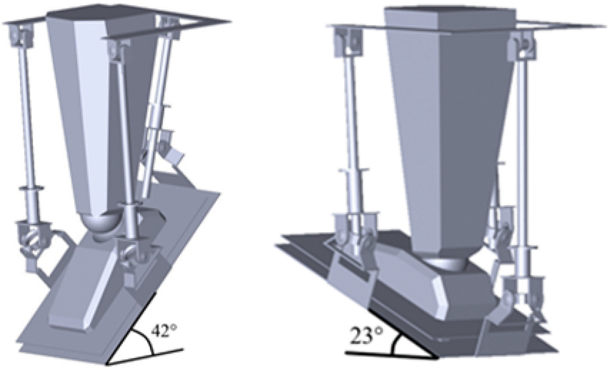

Fig. 7. Mode of operation - plantar – dorsiflexion.

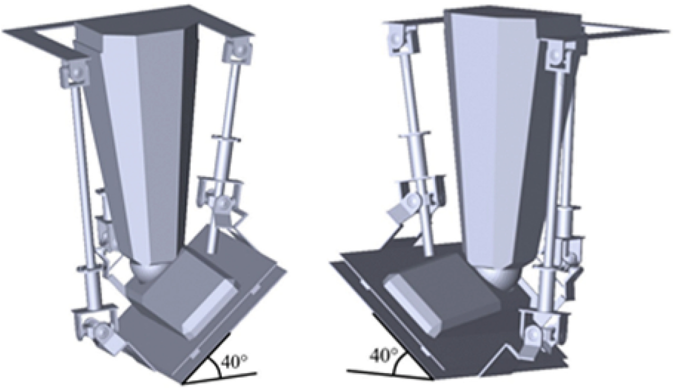

Fig. 8. Mode of operation - Pronation – supination.

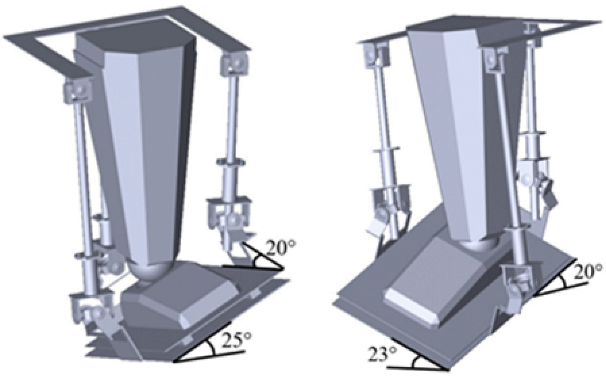

Fig. 9. User-configured operating mode.

are sensitive to changes in the patient's condition in relation to both muscle function and functioning. The clarity of objectives and graded assessment allows rehabilitation goals to be formulated in an accessible format, which increases patient motivation and satisfaction with treatment.

It is important to correctly determine the predicted end result of rehabilitation in each individual case, as this is the basis for the subsequent comprehensive assessment of the effectiveness of rehabilitation.

At the same time, objective and informative criteria for the effectiveness of medical rehabilitation in various forms of occupational diseases have not been sufficiently developed and put into practice today. Meanwhile, data from domestic and foreign sources show that the levels of rehabilitation indicators are closely interrelated with the indicators of disability, mortality, morbidity, organization and quality of medical care and are directly related to qualitative and quantitative criteria that characterize public health.

7 Conclusion

On the basis of the research carried out in the article, the following scientific and practical results have been obtained:

- Computational schemes have been given, on the basis of which mathematical models describing kinematic and dynamic interactions of the device and the patient's leg have been constructed.
- The functional diagram of the device reflecting the structure of automatic control system is given and described.
- The operating modes of the device are described.

A prototype device is under development.

Acknowledgment. The work was supported by grant of Russian Science Foundation № 22–21-00464 – "Development of models and control algorithms for biotechnical walking systems".

References

1. Pechurin, A., Fedorov, A., Jatsun, A., Jatsun, S.: Mathematical modelling of human walking in a rehabilitation exoskeleton using video gait analysis method. In: Proceedings of Southwestern State University, vol. 25, no. 3, pp. 27–40 (2022)
2. Karlov, A., Postolny, A., Fedorov, A., Jatsun, S.: Modeling an exoskeleton with a hybrid linear gravity compensator. In: Proceedings of Southwestern State University, vol. 24, no. 3, pp. 66–78 (2020)
3. Dmitriev, V., Fedorov, A.: Analysis of industrial exoskeleton qualitative performance based on a set of criteria. Issues in the methodology of natural and technical sciences: contemporary context, pp. 131–135 (2019)
4. Antipov, V., Karlov, A., Fedorov, A.: Energy distribution in the human-exoskeleton system. Issues in the methodology of natural science and engineering: contemporary context, pp. 109–112 (2019)

5. Pechurin, A.S., Jatsun, S.F., Fedorov, A.V., Jatsun, A.S.: Studying the two-legged walking system with video capture methods. In: Chugo, D., Tokhi, M.O., Silva, M.F., Nakamura, T., Goher, K. (eds.) CLAWAR 2021. LNNS, vol. 324, pp. 3–12. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-86294-7_1
6. Jatsun, S., Yatsun, A., Fedorov, A., Saveleva, E.: Simulation of static walking in an exoskeleton. In: Ronzhin, A., Shishlakov, V. (eds.) Electromechanics and Robotics. SIST, vol. 232, pp. 49–60. Springer, Singapore (2022). https://doi.org/10.1007/978-981-16-2814-6_5
7. Knyazev, A., Jatsun, A., Fedorov, A.: Mathematical modeling of the biomechanical rehabilitation system of foot exoskeleton in frontal and sagittal planes. In: Ronzhin, A., Pshikhopov, V. (eds) Frontiers in Robotics and Electromechanics. Smart Innovation, Systems and Technologies, vol. 329, pp. 19–32. Springer, Cham (2023). https://doi.org/10.1007/978-981-19-7685-8_2
8. Knyazev, A., Yatsun, S., Fedorov, A.: Control of a Device for mechanotherapy of the ankle joint. Biomed. Eng. **56**, 392–396 (2023)
9. Knyazev, A., Jatsun, S., Fedorov, A.: Algorithm of personalized adjustment of the active-passive mechanotherapy device for the ankle joint. In: International Conference on Industrial Engineering, Applications and Manufacturing, pp. 661–666 (2023)
10. Hassan, M., Khajepour, A.: Optimization of actuator forces in cable-based parallel manipulators using convex analysis. IEEE Trans. Rob. **24**, 736–740 (2008)
11. Alvarez-Perez, G., Garcia-Murillo, A., Jesús Cervantes-Sánchez, J.: Robot-assisted ankle rehabilitation: a review, disability and rehabilitation. Assist Technol. **15**(4), 3e94-408 (2020)
12. Antonellis, P., Galle, S., Clercq, D., Malcolm, P.: Altering gait variability with an ankle exoskeleton. PLoS One **13**(10), 0205088 (2018)
13. Jamwal, P., Hussain, S., Xie, S.: Restage design analysis and multicriteria optimization of a parallel ankle rehabilitation robot using genetic algorithm. IEEE Trans. Autom. Sci. Eng. **12**(4), 1433–1446 (2014)
14. Tsoi, H., Xie, Q.: Design and control of a parallel robot for ankle rehabiltation. In: 15th international conference on mechatronics and machine vision in practice, pp. 515–520 (2008)
15. Vallés, M., Cazalilla, J., Valera, Á.: A 3-PRS parallel manipulator for ankle rehabilitation: towards a low-cost robotic rehabilitation. Robotica **35**, 1939–1957 (2017)
16. Zeng, X., Zhu, G., Zhang, M.: Reviewing clinical effectiveness of active training strategies of platform-based ankle rehabilitation robots. Healthcare Eng. **2018**, 1–12 (2018)
17. Zhang, M., McDaid, A., Veale, A.: Adaptive robot with trajectory tracking control of a parallel ankle rehabilitation joint-space force distribution. IEEE Access **7**, 812–820 (2019)
18. Shevko, D.: Adaptive management in the conditions of undefinition. Sci. Rev. Tech. Sci. **2**, 75–77 (2017)
19. Yatsun, A., Karlov, A., Malchikov, A., Jatsun, S.: Investigation of the dynamical characteristics of the lower-limbs exoskeleton actuators. In: MATEC Web of Conferences. EDP Sciences, vol. 161, pp. 3–8 (2018)