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Type synthesis and preliminary design of devices supporting lower limb's rehabilitation

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Purpose: Based on the analysis of existing solutions, biomechanics of human lower limbs and anticipated applications, results of considerations concerning the necessary number of degrees of freedom for the designed device supporting rehabilitation of lower extremities are presented. An analysis was carried out in order to determine the innovative kinematic structure of the device, ensuring sufficient mobility and functionality while minimizing the number of degrees of freedom. Methods: With the aid of appropriate formalised methods, for instance, type synthesis, a complete variety of solutions for leg joints were obtained in the form of basic and kinematic schemes, having the potential to find application in devices supporting lower limb rehabilitation. Results: A 3D model of ankle joint module was built in Autodesk Inventor System, then imported to Adams and assembled into a moving numerical model of a mechanism. Several conducted simulations resulted in finding the required maximum stroke of the cylinders. Conclusions: A comparison of the angular ranges of ankle joint and similar devices with the ones achieved by the designed device indicated a sufficient reserve allowing not only movements typical of gait, but approximately achieving the passive range of motion for the ankle joint.

Key words: *simulation, numerical model, kinesitherapy, type synthesis, three-dimensional design*

1. Introduction

From the viewpoint of mobility, as well as rehabilitation, reproduction of movements for some of the leg's degrees of freedom (DOF) is much more important than for the others. Primarily, this is due to two factors: the range of motion (ROM) utilized in individual DOF [15] and the frequency of their usage during daily life activities (e.g., walking, getting up, sitting down), as well as in the rehabilitation process. Therefore, justifiable is analysis, among others, of the factors mentioned, in order to determine the innovative kinematic structure of the device, ensuring sufficient mobility and functionality while minimizing the number of DOF [7]. For this reason, the aim is also to create a complete base of structures for the limb joint modules, including all possibilities in the range of assumptions. This goal will be achieved by applying a formalised method based on the type synthesis to obtain a complete variety of solutions in the form of sets of basic and kinematic schemes.

2. Materials and methods

2.1. Determining the mobility of the designed device's structure

From the perspective of biomechanics, human leg has 30 DOF. Nevertheless, after simplifying leg's movement and omitting DOF located in the foot, responsible among others, for the movements of toes, kinematic structure can be reduced to basic seven DOF (Fig. 1), which allows the realization of the presented leg's movements [5]. After simplification of

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the leg structure to 7 DOF, one can distinguish three of them that are essential and necessary for proper performance of the basic tasks such as sitting down, getting up and walking. These DOF are indicated in Fig. 2 as: R_X^H, R_X^K, R_X^A, and enable leg's flexion/extension in three joints in the sagittal plane. Furthermore, expedient is taking into account the movements of abduction/adduction at the hip joint (R_Z^H) and inversion/eversion at the ankle joint (R_Z^A). Justifiable may, however, be the omission of two DOF marked as R_Y^H and R_Y^K, allowing a similar movement, internal/external rotation of the leg in the longitudinal axis. Of course, their omission has a certain negative impact on the device's capabilities of motion and rehabilitation, but it is inconsiderable due to the relatively rare usage of these DOF.

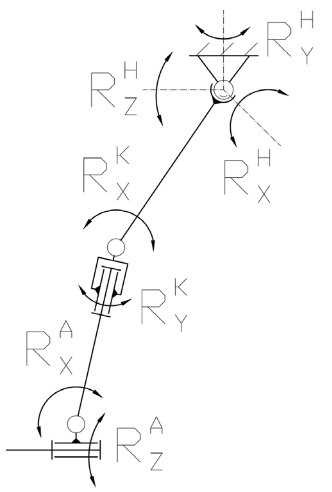

Fig. 1. Simplified kinematic structure of the human lower limb – 7 DOF

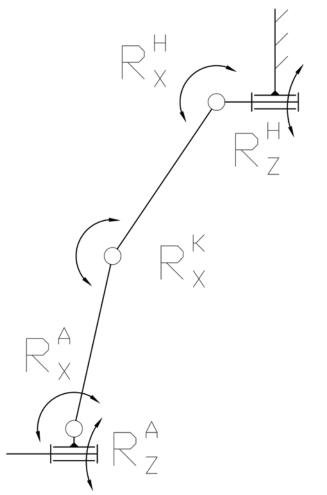

Fig. 2. Kinematic structure of the human lower limb accepted for analysis – 5 DOF

Exactly this kind of a minimalist approach focusing on the aforementioned basic activities is realized by the design of the Austin exoskeleton, which in 2011, was developed by UC Berkeley, as a low-cost exoskeleton for restoring mobility of paraplegics. In order to reduce the cost, the exoskeleton's design was focused only on the most important daily life activities and simplicity of the construction. The device consists of steel legs and only one motor for each leg, which means that the mechanisms of the hip and knee are coupled and powered by a single motor. Austin is expected to cost around $15,000, whereas other devices with similar abilities may cost more than $100,000 and are predestined to be applied in clinics rather than at homes [3]. A similar example, in favour of the existence of the need and trend for simplifying structures of the devices supporting lower extremities, is a low-cost exoskeleton developed at LARM, University of Cassino and South Latium, Italy [6].

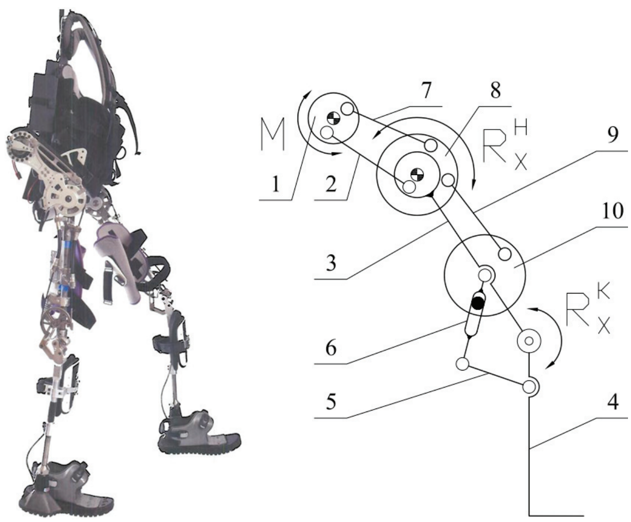

Fig. 3. Austin exoskeleton – general view and kinematic diagram of one leg [3]

A different device is then the BLEEX exoskeleton developed in 2004 by UC Berkeley. It is a lower limbs anthropomorphic exoskeleton augmenting the strength as well as endurance of people, carrying heavy loads or walking great distances, such as soldiers, disaster relief workers and emergency personnel [3]. BLEEX has 8 DOF, including one in the spine, but only 3 of them are powered by hydraulic cylinders (Fig. 4). For the unpowered DOF, steel springs and elastomers have been used [10]. The potential usage in the medical field (physical rehabilitation) had been early realized and resulted in the development of eLegs and Ekso exoskeletons for paraplegics rehabilitation [3].

Summarizing, it can be stated that the simplification of the human leg's kinematic structure to presented 7 DOF is correct and reasonable from the point of view of the device designed for rehabilitation of the lower limb. In addition, the search for kinematic structure was limited to cases having the mobility of five, i.e., without the two rotations mentioned (R_Y^H, R_Y^K). In order to maintain adequate simplicity and functionality of the whole mechanism for the assumed number of DOF, it is possible to divide the entire mechanism into individual modules, which will reduce the mobility and thus the complexity of these modules.

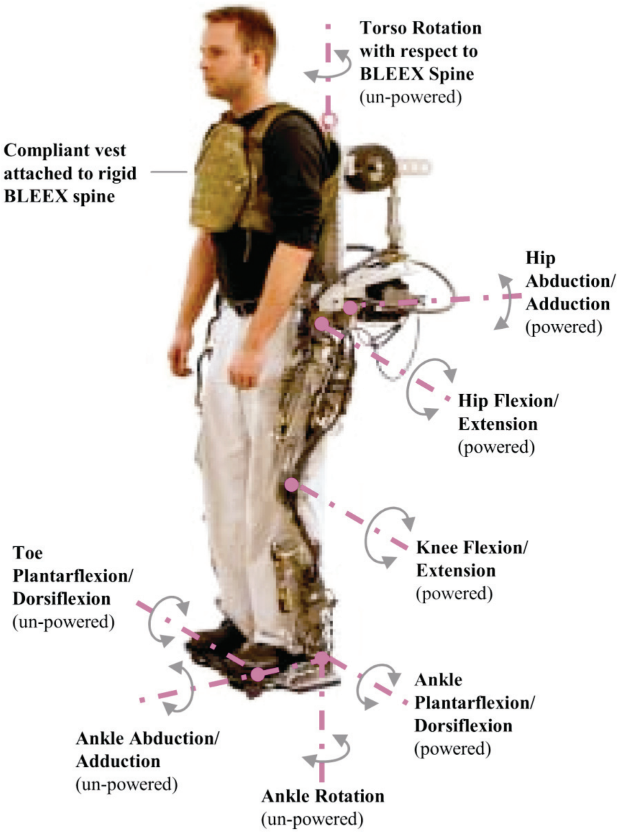

Fig. 4. View of BLEEX [10]

2.2. Synthesis of the kinematic structure of the device

2.2.1. Initial assumptions of the type synthesis

In order to find the innovative structure of the designed device's kinematic system, to systematize solutions and obtain all possible solutions in the range of assumptions, the problem of synthesis of the mechanism was examined in a wide range. It was decided not to include the leg's joints as part of the device's kinematic structure to protect them from additional burden. Furthermore, the search for solutions in the form of parallel mechanisms, which are characterized by high rigidity, repeatability of movement and ability to carry heavy loads, was carried out. On the other hand, because of the desire to achieve modular structure and mobility, the development of the mechanism's kinematic structure for each leg's joint was conducted. The intermediate chain method [9] and a method for type synthesis of parallel mechanisms based on usage of several branches (the branches method) [2] connecting the base and the driven link were applied. Appropriate assumptions and constraints have been introduced in each case. Due to the similarities in the functioning of certain solutions using actuators or rotary motors, the presented schemes were limited in these cases to solutions with one type of drive.

2.2.2. Synthesis of the parallel structure for the hip and knee joint module

One of the possible examined solutions was a parallel mechanism allowing separate movements of the hip and knee joints in the sagittal plane, anticipating that providing the other movements could be achieved with an additional module. Resulting from the desired movements (R_X^H, R_X^K), the required final mobility of the entire mechanism must be equal to 2. In this case, also an assumption has been made that one of the intermediate chain's links will be a variable length element. Replacing one of the two-node parts with a drive in the form of an actuator will increase the mobility of the chain by 1. For this reason, intermediate chains with mobility $W = 1$ should be searched for. Driven link "b" has been attached to the base "o" using an additional two-node link (Fig. 5), resulting in mobility of the driven link $W_b = 2$. As a result of these assumptions, since

$$W = W_b + W_U, \tag{1}$$

$$W_U = 3k - 2p_1 - 1p_2, \tag{2}$$

after transformations equation (3) was obtained

$$3k + 1 = 2p_1 + 1p_2 \tag{3}$$

where W_U – mobility of U chain, k – the number of moving parts in the intermediate chain; p_i – the number of the kinematic pairs of i-class.

Due to the large number of potential solutions, it was necessary to introduce suitably tight constraints: $1 \le k \le 3$, $p_1 \ge 2$, the number of class I translational joints $p_{1P} \le 1$, $p_2 = 0$, the elements' number of nodes limited to three, the number of two-node elements $N_2 \ge 1$.

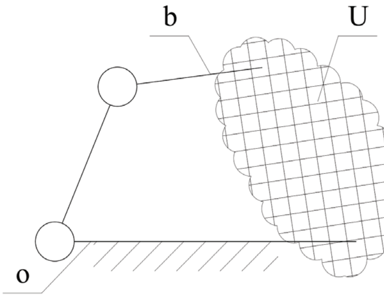

Fig. 5. The initial assumptions for the synthesis of the hip and knee joints

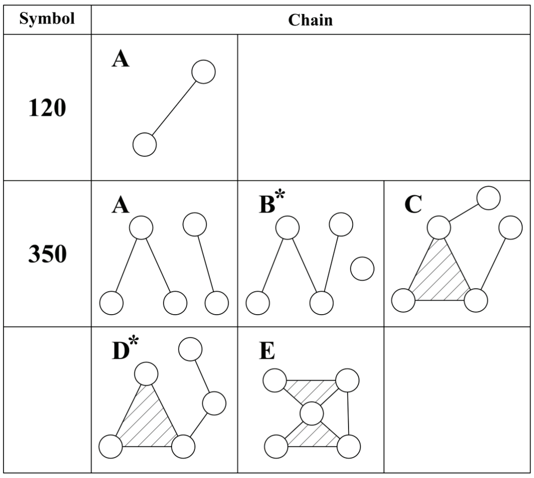

Fig. 6. Graphic forms of intermediate chains for chosen solutions

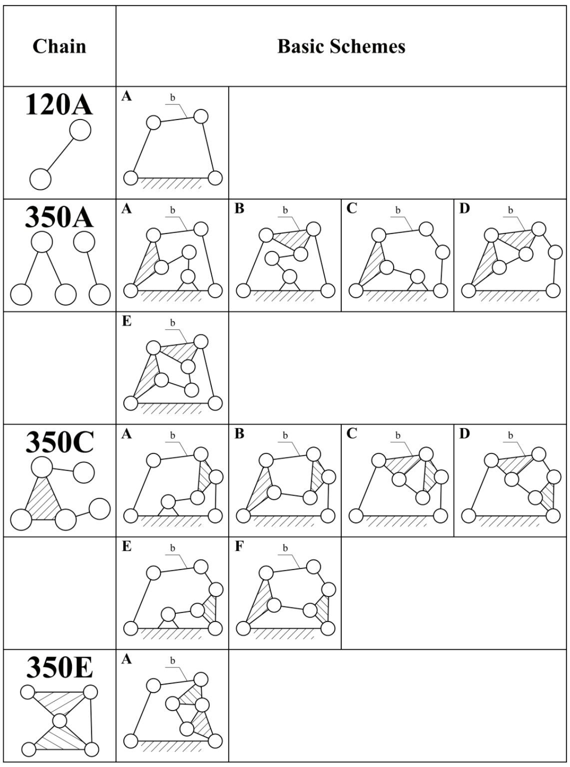

Fig. 7. Basic schemes for the case currently considered

On the basis of assumptions and equation (3) the possible solutions and graphic forms of intermediate chains (Fig. 6) were found. It should be noted that solutions 350B and 350D (additionally marked with "*"), after being used to create the basic schemes, do not give any proper solutions fulfilling the assumptions. For this reason, incorrect solutions, characterized by, for example, a non-uniform mobility, at this stage were omitted and not presented among the basic schemes (Fig. 7). In the further part of the type synthesis similar actions were taken and even the graphic forms of chains were not presented if after considerations they did not provide correct solutions.

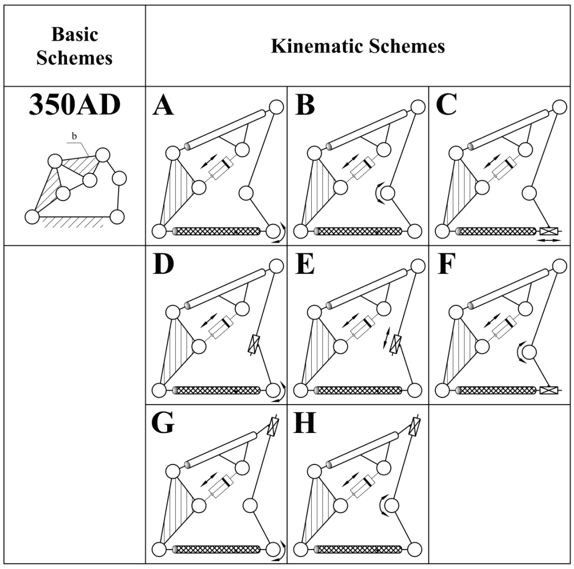

Fig. 8. Kinematic schemes with drives

Finally, the possible solutions in the form of kinematic schemes, following the previous assumptions, were found for the selected basic scheme 350AD (Fig. 8). Only the correct solutions, which theoretically may find a real application in the designed device were presented.

2.2.3. Structure's synthesis for the knee joint's module

A separate device's module for the knee joint was also designed. In the knee joint, besides the main rotation of the shank relative to the thigh (R_X^K in Fig. 2), there is also an additional translational movement caused by slipping. Together with the leg's flexion and the change of the rotation angle in the joint, the position of the axis of rotation is changing. In mechanics such movement may be reproduced using a cam joint that is a second class pair. Therefore, the knee joint could be regarded as a pair with two DOF.

For the above reasons, it can be assumed that the mechanism required in this case, should have mobility $W = 1$, but taking into account the complex movements in the knee joint and the possibility of introducing an additional DOF, which, if necessary, may provide a better realization of the actual motion in the knee joint. The starting point for the synthesis is shown in Fig. 9, where the driven link is free, so it has three DOF ($W_b = 3$). In this case, the topology of the U-chain is described by the following equation

$$3k + 2 = 2p_1 + 1p_2 . \quad (4)$$

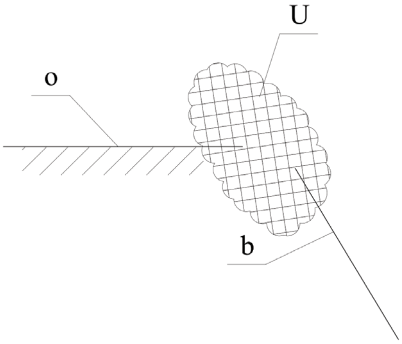

Fig. 9. The initial assumptions for the synthesis in the case of the knee joint

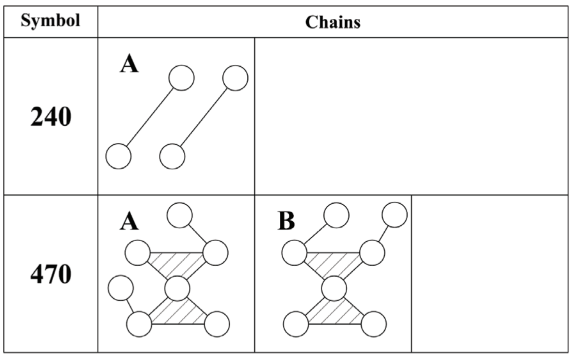

Fig. 10. Graphic forms of intermediate chains for chosen solutions

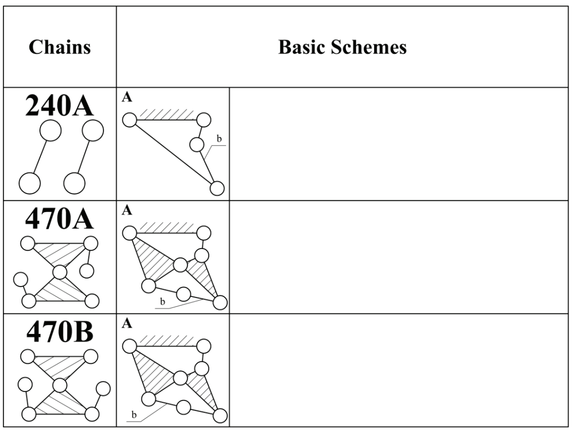

Fig. 11. Basic schemes for the case currently considered

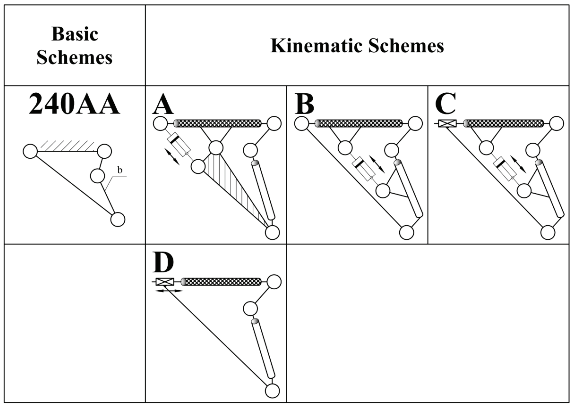

Fig. 12. The set of kinematic schemes with drives

Equation (4) has been used, with the constraints as in section 3.2, to generate graphical forms of intermediate chains and the basic schemes (Figs. 10 and 11).

For the selected scheme 240AA, the possible solutions in the form of kinematic schemes are presented (Fig. 12). At the current stage, the form of the mechanism's part responsible for the complex movement in the knee joint has not yet been precisely specified. For this reason, both kinematic pairs were presented as rotational.

2.2.4. Structure's synthesis of the module for the ankle joint

When focusing on designing the module for ankle rehabilitation, it was concluded that for this device a spatial kinematic chain is required. This is due to the fact that the two degrees of freedom (R_X^A, R_Z^A) existing in the joint enable movement in two approximately perpendicular planes. For this reason, the mobility of the whole mechanism should be equal to two ($W = 2$) and mobility $W_b = 6$, since the driven link is not connected to the base (Fig. 13).

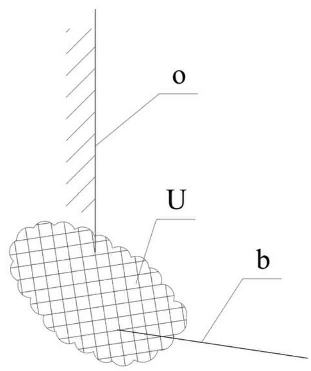

Fig. 13. The initial assumptions for the synthesis of the serial chain in the case of ankle joint (the intermediate chain method)

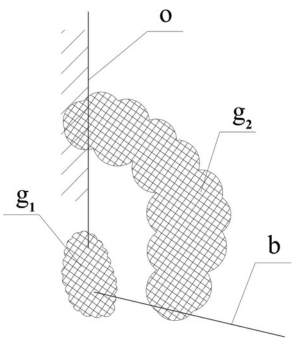

Fig. 14. The initial assumptions for the synthesis of the parallel chain in the ankle joint case (the branches method)

In the case of this joint, besides the intermediate chain method (Fig. 13 and equation (5)) the second mentioned method for the type synthesis of parallel mechanisms, based on the division of the intermediate chain into two branches (g_1, g_2 in Fig. 14) was used. It was assumed that the mechanism consists of exactly two branches having the same mobility. For this reason, the mobility of each branch is equal to half of the entire chain's mobility (equation (6)). In both cases, the following constraints were introduced: $k \leq 3$, $p_2 \leq 2$, $p_3 \leq 1$, $p_4 = p_5 = 0$.

$$6k + 4 = 5p_1 + 4p_2 + 3p_3, \tag{5}$$

$$6k + 2 = 5p_1 + 4p_2 + 3p_3. \tag{6}$$

Again the possible solutions of intermediate chains in the graphic forms and basic schemes were obtained, using equation (5) (Figs. 15, 16) and equation (6) (Figs. 17, 18), respectively.

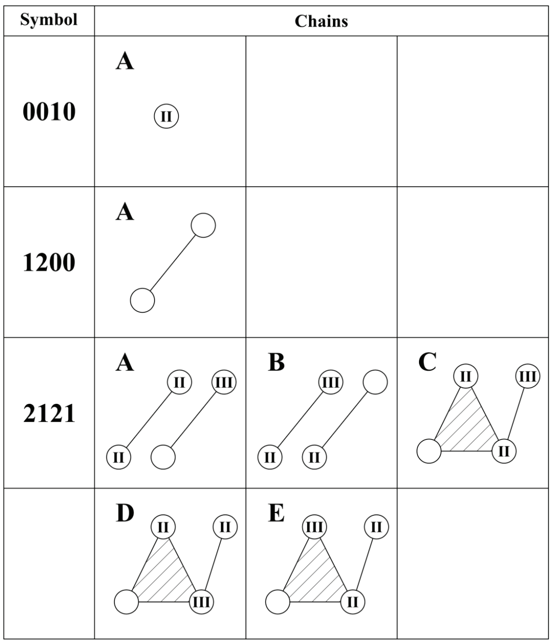

Fig. 15. Graphic forms of the intermediate chains (according to equation (5))

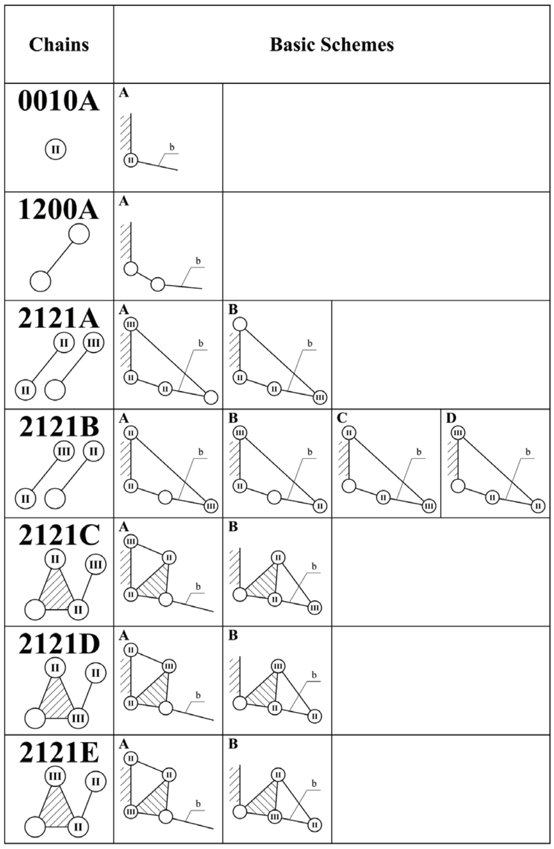

Fig. 16. Basic schemes (according to equation (5))

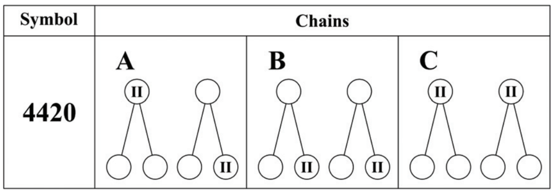

Fig. 17. Graphic forms of the intermediate chains (according to equation (6))

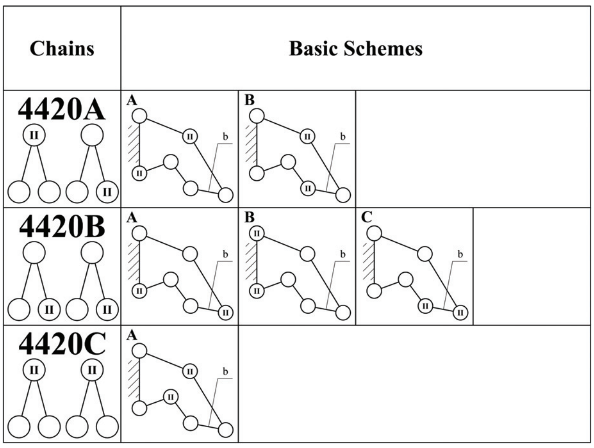

Fig. 18. Basic schemes (according to equation (6))

Finally, among the basic schemes of the two methods, the case 1200AA (Fig. 16) was selected in order to find for it solutions in the form of kinematic schemes (Fig. 19).

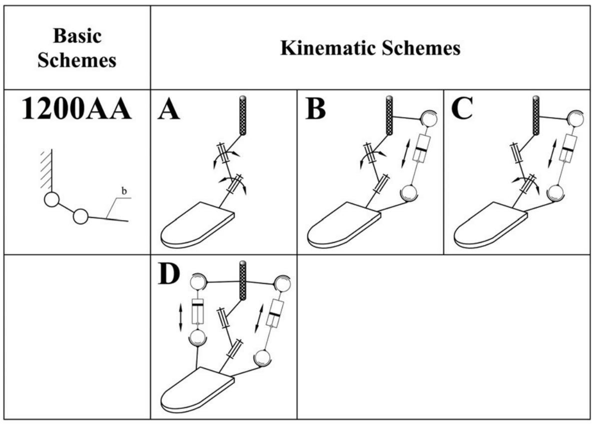

Fig. 19. All possible kinematic schemes for the solution 1200AA, ankle joint module

3. Results

3.1. Mechanical model of chosen structure for ankle joint support

Focusing on the ankle joint, for the kinematic scheme 1200AAD, a mechanical solution was carried out in the form of a designed 3D model in Autodesk Inventor System (Fig. 20). Then individual parts were imported to Adams and assembled into a numerical dynamic model (Fig. 21), in order to verify the correctness of its operation. Dimensions of the mechanism's particular elements were adjusted to fit the human lower limb. These dimensions were based on anthropometric data for the body segments' lengths expressed in proportion to the user's height [15], assumed in this case equal to 186 cm.

Fig. 20. View of the mechanism 3D model in Autodesk Inventor System

Fig. 21. View of the mechanisms computational model in Adams

One of the most important features of the designed module, whose correctness has to be verified, is the attempt to adjust the directions of the device joints' axes of rotation to the directions of the leg joints' axes of rotation, in order to more accurately reproduce human movements. Since angles of the rotational axes' deviation from the foot's middle line and horizontal line are individual for each person, average values were used. In addition, due to the mentioned fact, complex motions of cylinders were necessary to achieve separated movements of the foot, in contrast to a similar rehabilitation device Anklebot [8]. In order to obtain the characteristics of cylinders length change during the foot movement, for the Adams model, three simulations were conducted using inverse kinematics, i.e., the movement was forced in the ankle joints rather than by the cylinders.

First simulation assumed a separate movement of dorsiflexion/plantarflexion in the range of about –45° to 45°. In the used motion the angular acceleration was controlled, accordingly to the appropriate equations (7) and (8) [14], in order to obtain smooth characteristics of angular acceleration, angular velocity and change of angle in the ankle joint (Fig. 22). Total stroke for the first cylinder in this case was equal to nearly 129 mm and for the second cylinder to about 212 mm (Fig. 23).

$$\varepsilon(t) = \frac{2\pi\alpha}{T^2}\sin\left(\frac{2\pi(t-t_s)}{T}\right) \tag{7}$$

where $\varepsilon(t)$ – angular acceleration, α – angle of rotation in the considered phase of movement, T – time

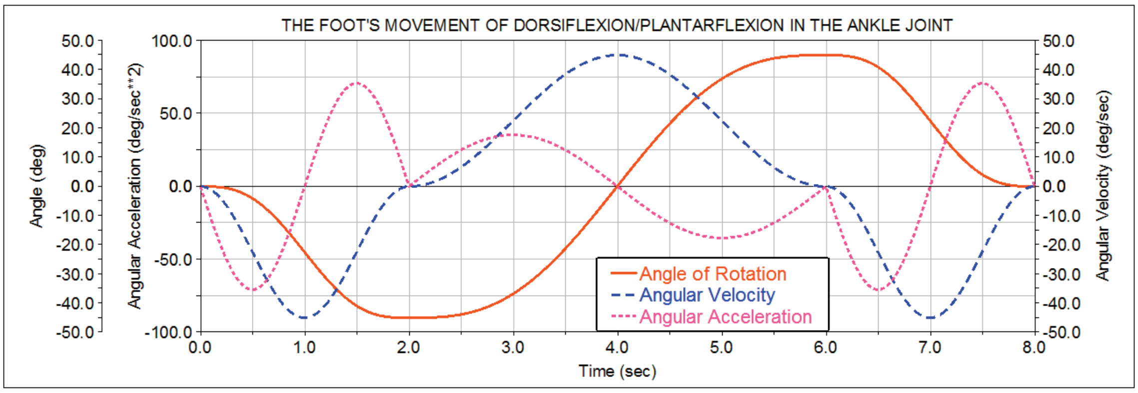

Fig. 22. Characteristics of movement in the ankle joint for separate dorsi/plantar flexion

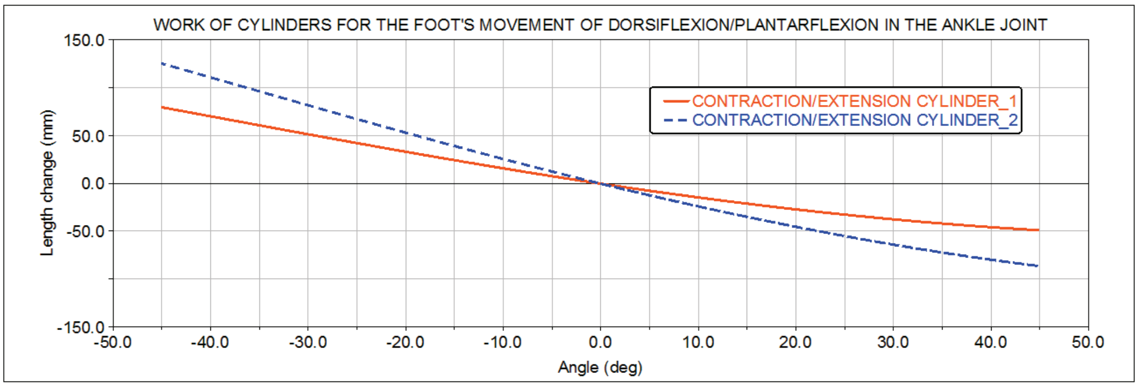

Fig. 23. Length of cylinders for separate dorsi/plantar flexion in the ankle joint

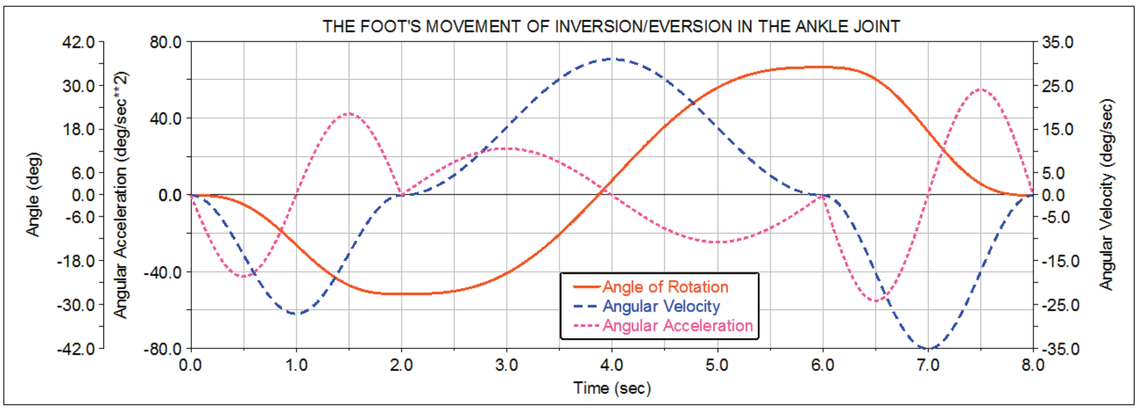

Fig. 24. Characteristics of movement in the ankle joint for separate eversion/inversion

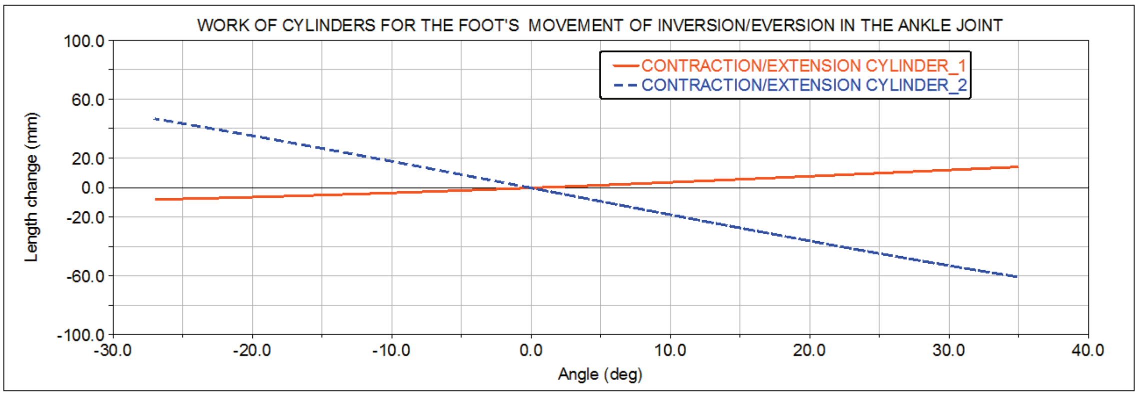

Fig. 25. Length of cylinders for separate eversion/inversion in the ankle joint

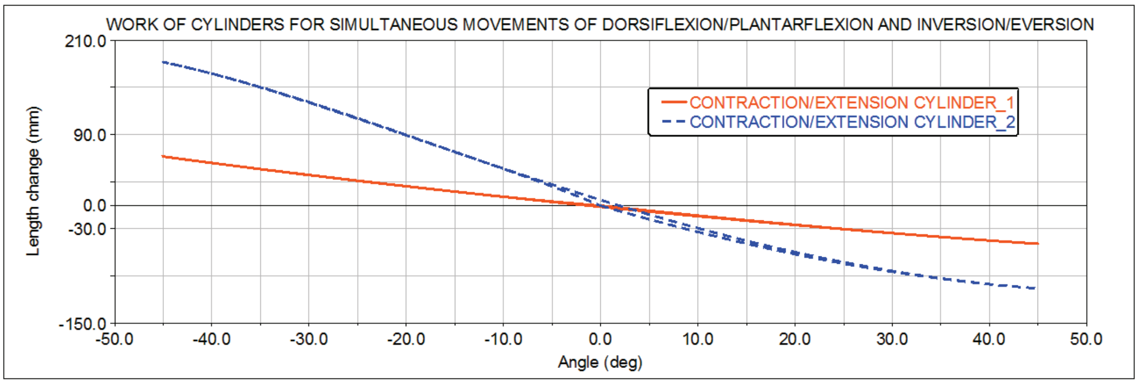

Fig. 26. Length of cylinders for simultaneous dorsi/plantar flexion and eversion/inversion in the ankle joint

of the movement in the phase considered, t – time, t_s – starting time of the movement in the phase considered.

In example (R_X^A) considered,

$$\varepsilon(t)=\begin{cases}0\le t\le 2 => T=2s, & \alpha=45°, \quad t_s=0,\\ 2\le t\le 6 => T=4s, & \alpha=90°, \quad t_s=2,\\ 6\le t\le 8 => T=2s, & \alpha=45°, \quad t_s=6.\end{cases} \quad (8)$$

Another simulation was the separated movement according to the second axis of rotation in the ankle joint, resulting in the eversion/inversion in the range of approximately –27° to 35°. A similar characteristic of the angular acceleration was used (equations (7), (9) and Fig. 24). In this case, the values of cylinder strokes were equal to about 22 mm (cylinder 1) and nearly 108 mm (cylinder 2).

In example (R_Z^A) considered,

$$\varepsilon(t)=\begin{cases}0\le t\le 2 => T=2s, & \alpha=27°, \quad t_s=0,\\ 2\le t\le 6 => T=4s, & \alpha=62°, \quad t_s=2,\\ 6\le t\le 8 => T=2s, & \alpha=35°, \quad t_s=6.\end{cases} \quad (9)$$

The last simulation was a combination of both previous movements obtained with the simultaneous dorsiflexion/plantarflexion and inversion/eversion movements according to appropriate axes of rotation. This simulation showed that the first and second cylinder strokes were equal to about 112 mm and 289 mm, respectively.

The results of the performed simulations indicate that the required maximum stroke of the cylinders is equal to approximately 289 mm. Runs of cylinders' length changes indicate the possibility of controlling the system, since the strokes are sufficient to achieve appropriate resolution control for both of the assumed movements (rotations).

4. Discussion

Based on the analysis of existing solutions, human lower limb's biomechanics and anticipated applications, it was determined that reduction in the number of necessary DOF, for the device supporting rehabilitation of lower extremities, is possible. With the aid of appropriate methods, a variety of solutions for particular leg's joints was obtained in the form of basic and kinematic schemes, having the potential to find application in such devices. Three-dimensional models of the chosen ankle joint's module were built in Autodesk Inventor System and Adams, with the device's axes of rotation compatible with the ones in the human leg's joints. In addition, several simulations were conducted for simultaneous and separate movements of the foot in both ankle joint's axes of rotation, resulting in finding the maximum required stroke of the cylinders.

The study of angular motion achieved during movement in individual joints is important especially in the case of various kinds of limb's diseases. Knowledge of the particular joints' ROM, as well as changes in the obtained angles of rotation is vital for selecting the appropriate process of rehabilitation for the patient. In studies [4], [12], data concerning the lower limb's individual joints' ROM, but only for the gait stereotype, is presented. Whereas, the joint's passive ROM is significantly larger, which is also confirmed in [12], showing differences of the achieved angles in all leg's joints, for patients with degenerative changes of the knee joint. In some cases, e.g., the ankle joint's ROM in sagittal plane was shifted towards the dorsiflexion, causing an increase in its maximum angle (excessive dorsiflexion). In work [11], overall characteristics of gait kinematics for the ankle joint's dorsi/plantar flexion are similar to those in [12]. The results in [11] confirm that the ankle joint's ROM utilized during gait may be changed for instance by the type of training or even by the device itself. The mass of equipment can alter the gait characteristics and this influence would need to be investigated for authors' designed device in case of adapting it to gait training. In addition, during the rehabilitation process often the most important is to restore the maximum ROM in the joint. Therefore the rehabilitation device requires a significantly larger ROM than the one utilized during typical gait and more appropriate are data from [1]. The ROM achieved in [1] for squats or stair-climbing is more suitable, since during these demanding tasks the maximum ROM of angles is reflected more reliably.

In the authors' own research, the simulations of movements and measurements for anatomical ankle joint's axes of rotation were made in contrast to [11], [12] where movements according to the anatomical planes were considered. Since directions of the axes were not perpendicular to the planes (rotated according to two planes) the obtained characteristics of angles in the joint were not similar to the ones presented in [11], [12]. Another difference is the type of movements investigated. The designed device was tested with the angles' values corresponding to maximum ROM in the joint (passive ROM) rather than the movements (angles) during gait. Therefore, the runs of angles' changes during movement from [11], [12] and from the authors' own research could not be directly confronted in this case.

Nevertheless, comparing the obtained angular ranges from the aforementioned sources with the ones achieved by the authors' designed device indicates that the device has a sufficient reserve allowing not only movements typical of gait, but approximately achieving the passive ROM for the ankle joint. This view is also supported in [13] by the features of a bio-inspired soft wearable robotic device for ankle–foot rehabilitation based on artificial muscles.

This prototype is able to perform the movement of dorsi/plantar flexion with maximum of 14° and 13°, respectively [13], which constitutes to about a quarter of the possible ROM of the authors' designed device. The obtained results show that on the basis of the built numerical and 3D models, the innovative solution for the ankle joint module could be determined.

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