HUMAN FOOT MOTION SIMULATION DURING WALKING

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Abstract: *The ability of a person to move quickly plays an important role in the modern, constantly accelerating world. Despite the good development of the infrastructure of large cities, a significant part of its population uses underground or ground public transport, mixing daily trips on it with walking. That is the only one fact, where the importance of the process of walking in the life of modern man can be noticed. There is a new method for evaluation of therapeutical rehabilitation complex work for human lower limbs motion recovery is introduced. Simple mathematical basis and ethalon criterias for rehabilitation complex prototype efficency control are shown.*

Keywords: HUMAN PATH REHABILITATION, 3D MODELLING, FOOT MOTION IMITATION, LOWER LIMBS KINEMATICS AND DYNAMICS

1. Introduction

A huge role in the gait of a person is played by the foot. Being a link between the plane of motion and the physical body of a person, it performs many important functions, the main of which are direct movement of a person in space and maintaining balance / support of body weight. It is logical to assume that the study of such an interesting topic as the movement of a human being during walking should begin with the study of the foot motion. Having a model of the already designed mechanism of a prototype simulator for restoring the movement of a person's lower limbs (described in section 2), it is of particular interest to study how precisely the muscle groups responsible for the walking process will be subjected to useful loads. If the training of muscle groups, flexing and extending the legs in the hip and knee (sagittal plane) seems to be implemented quite well, the efficient training of the muscles responsible for the flexion / extension of the foot remains questionable. This work has two main objectives, the first of which is the establishment and finding of mathematical criteria for assessing the "success" of the rehabilitation mechanism work. In other words, it is necessary to establish a “corridor” of variable parameters of the designed prototype of the simulator, or in other words, quite successfully simulate the gait of a healthy person. The second goal is to identify proposals for making structural changes to the prototype model and to determine future directions for product improvement. This work continues the cycle of works aimed at studying the movement of a person while walking [1-6].

2. The Design of the Mechanism of the Training Device for Gait Restoration

In order to simulate the gait of a person, as well as to keep in mind the possible future creation of a prototype of a medical exercise machine for movements of the lower limbs restoration, the construction based on the model of an exercise bike was chosen. The main idea is to use a reverse-action exercise bike as the basis for the designed prototype of the rehabilitation training device, by the way using the engine to set the movement parameters of a person's legs, and not oppositely. The conventional picture of the 3D model of the mechanical part of the designed product is presented below. The specified assembly consists of 2 subassemblies. The number 1 denotes the welded supporting construction of the training device, the number 2 denotes the prototype pedal rotation mechanism.

Subassembly 1(Fig. 2) consists of 4 elements and plays the role of a supporting frame with bushings for fitting bearings into them. The height of the sleeves is adjusted depending on the tasks of imitation, as well as the anthropometric parameters of a particular person and the stage of rehabilitation. The numbers denote: 3 - vertical plates, perceiving the load from the training device and the patient; 4 - bushings for pressing bearings into them (the connection of elements 3, 4 is formed by welding them together); 5 - stiffening ribs necessary for the stability of the position of the plates 3 (welded to the plates 3, 2 details on each plate), 6 - the base plate serving as protection against tilting / shifting of the exercise mechanism prototype and for more accurate positioning of the plates 3 and ribs 5 between themselves before welding (details 3,5,6 are welded together).

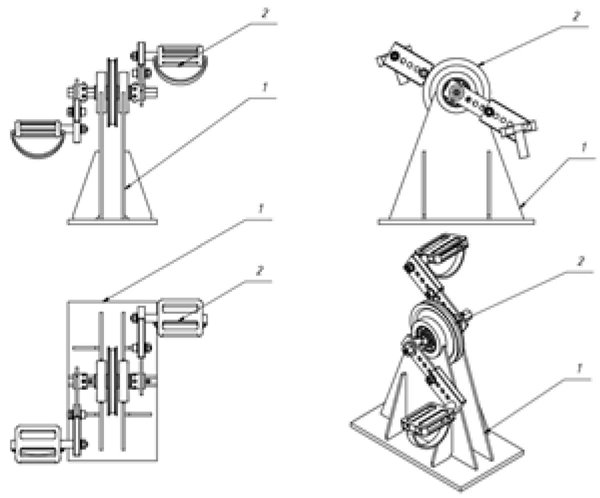


Fig. 1. *The design of mechanism of the training device / exercise machine for human lower limbs motions rehabilitaion.*

Next, we consider subassemblies 1 and 2 in more detail.

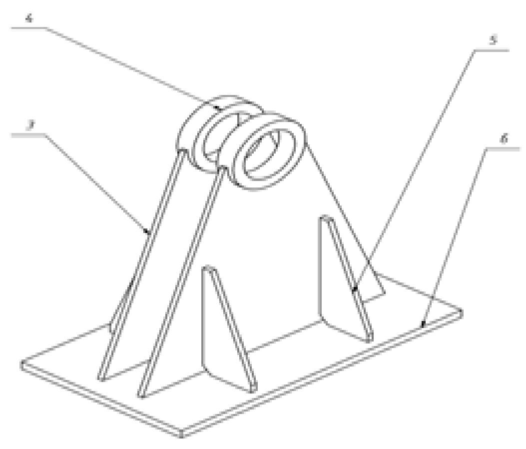


Fig. 2. *Load-Bearing construction of the prototype.*

Subassembly 2 (Fig. 3) consists of 2 different, lower-level assemblies, in other words 2 identical adjustable pedal assemblies 7 and one assembly 8, designed to transfer motion from engine to patient`s legs with a belt pulley at the base.

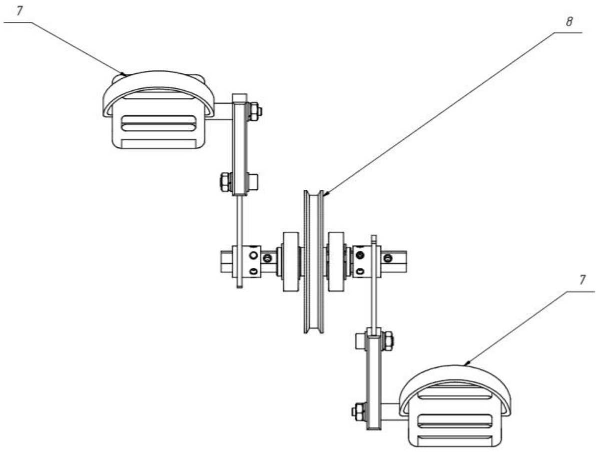


Fig. 3. *Moveable part of the prototype.*

Since the assemblies 7 and 8 that represent the main value of our prototype, they devote special attention.

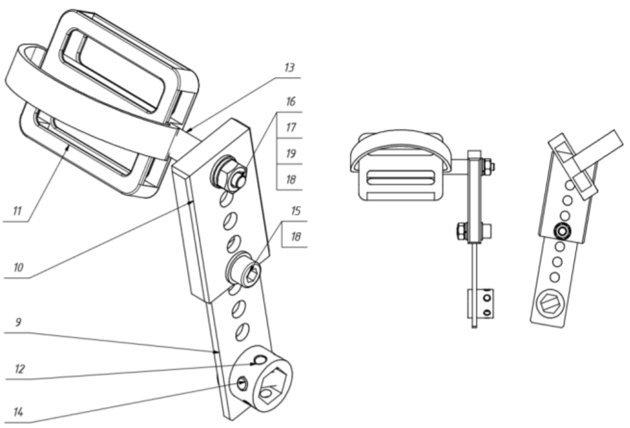


Fig. 4. *Pedal assembly.*

Figure 4 shows the so-called pedal assembly. The main elements of the pedal are plates 9 and 10, which regulate the heights of the steps of the left and right legs (in the figure you can see the holes for adjustment), the adapter to the hex rod 12, which is welded to plate 1 and with the help of which pedals can be mounted at angles from 0 to 180 degrees relative to each other.

The pedal 11 is equipped with an adjustable belt (conventionally depicted), which tightly fixes the patient's foot on the pedal. The pedal itself is worn on the threaded axle 16 and is fixed to the plate 10 with a nut 17, flat 18 (to better press and increase the pressure area when tightening the nut) and spring 19 (to prevent self-unscrewing of the threaded connection) washers. The plates for adjustment the height of the pedal / foot are inserted into each other and fastened with fasteners 15 (hex bolt), 17, 18, 19.

The last of the considered assemblies of the recovery training device prototype is the assembly 8, which performs the function of transmitting motion from the engine to the legs of the patient.

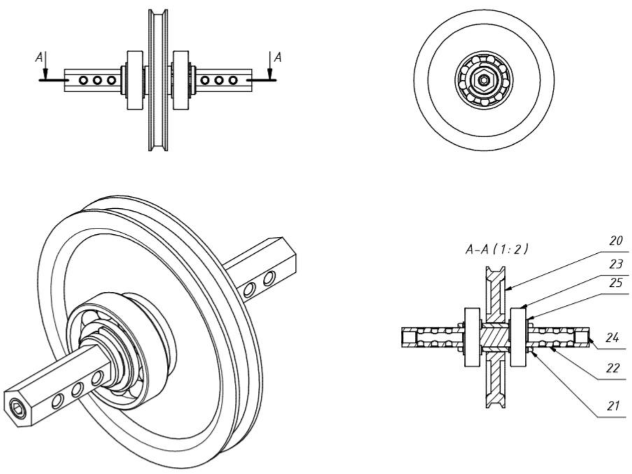


Fig. 5. *Mechanism for motion transfer from the engine to the legs of the patient.*

The mechanism consists of a pulley 20, which is worn on the sleeve 21 with the help of a key welded to it. The sleeve 21 has a hexagonal cutout inside, into which a hexagon 22 is inserted (available material). Bearings 23 are pressed into the sleeve from the both sides, which, in turn, are pressed into the bushings 4 (see above). Holes, threaded in hexagon 22, give a possibility to install the pedals at different angles, which will increase the range of possible rehabilitation exercises. Threaded stud 14 is necessary for the formation of the connection between the pedal and pulley mechanisms. The threaded stud 24 is provided to allow elongation of the hexagon 22.

The designed prototype of future exercise machine has the following variable parameters:

- Pulley / pedal rotation speed (set by motor)
- Distance between legs
- Height of legs lifting (can be set up for each of legs separately)
- Angle of pedals installation relatively to each other

3. Determination of the Main Parameters of the Human Gait, during the Operation of the Training Device Prototype. Used Mathematical Apparatus and Introduced Restrictions.

In order to determine the degree of compliance of physical parameters, it is necessary to distinguish mathematical models and limitations imposed on the work of the future exercise machine. The model described in the article [7] is one of the most applicable to our case from the decades of the studied mathematical models of a human gait.

As a part of a study conducted in the Sports Medicine Laboratory of the University of Tartu (Estonia), using a system of markers installed on the skin of the subjects, with the help of cameras and a power platform along which the tested women walked freely (4 women who are not athletes, surgeries and other pathologies of the skeletal-muscular and nervous system), the following spatial-temporal parameters of gait were obtained:

***Table 1** Anthropometric data of the survey persons. Rows of the table are having an information about age, weight, height, length of the lower limbs, hips, length from tibia to floor, length for tibia to ankle, length of the foot, width of the foot, width of the back side of foot, thigh size, constant parameter consequently.*

Наименование параметра	Обследуемые			
	B	M	P	A
Возраст, лет	28	22	28	26
Вес, кг	70,5	56,1	73,45	58,4
Рост, см	169,9	157	172,3	168,8
Длина нижних конечностей, см	102	87,5	98,5	100
Длина бедра, см	51,5	44,5	53,5	51,3
Длина голени до пола, см	50,5	42,5	45	48,7
Длина голени до лодыжки, см	43	37,5	40	42
Длина стопы, см	24,7	23,6	25,5	26,6
Ширина стопы, см	9,5	9,6	10,7	10,5
Ширина задней части стопы, см	7,2	6,2	6,7	6,4
Размер таза, мм	90	80	80	80
Параметр константности	0,5878	0,7159	0,3994	0,7095

Based on the data obtained, a kinematic scheme of movement of the human leg during the gait, presented in the form of a four-link mechanism, was formed (Fig. 6).

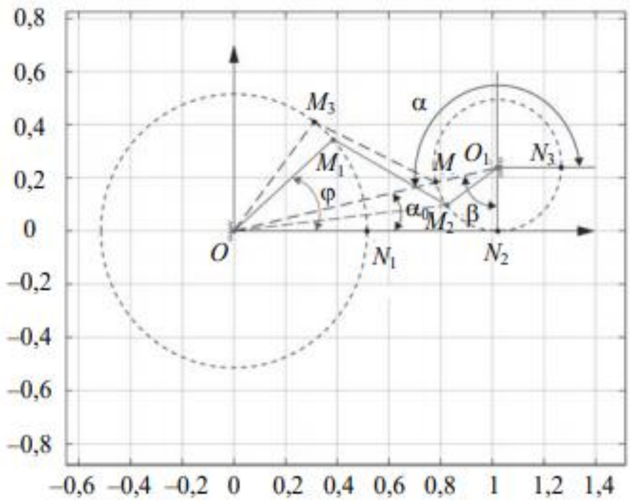


Fig. 6. *Kinematic scheme of the 4-link mechanism*

The following notation is introduced on the presented kinematic scheme: $OM_3 = OM_1 = l_1$ – thigh length; $O_1M = O_1M_2 = r$ – foot length; $M_3M = M_1M_2 = l_2$ – length of the tibia to floor; L – total length of the tibia and thigh; φ – the angle of rotation of the thigh; α_0 – fixed angle of the kinematic system; $\beta = \pi/2 - \alpha_0$; α – foot rotation angle; $x_1 y_1$ – point M_1 coordinates (current coordinates); $x_2 y_2$ – point M_2 coordinates (current coordinates).

The fixed angles of the kinematic system presented above denote both the goniometric parameters and the limiting configurations of the system before the completion of pushing the forefoot off the ground.

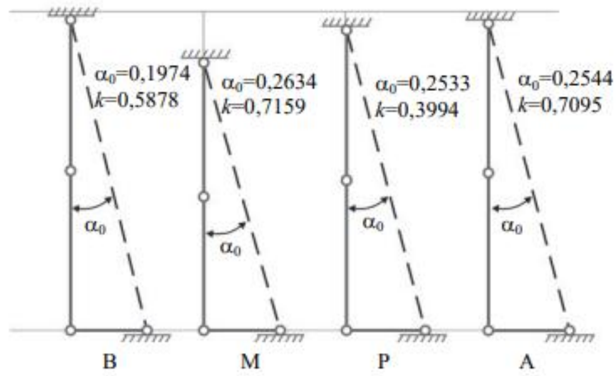
After determination of 5 links conditions: coordinates M_1, M_2, $z_1 = 0$, $z_2 = 0$ and equality:

$(x_2 - x_1)^2 + (y_2 - y_1)^2 = l_2^2 \rightarrow ((x_2 - x_1)^2 + (y_2 - y_1)^2 - l_2^2 = 0),$
we obtain the mechanical system with one degree of freedom.

Last equality is basic for constant parameter k calculation:

$$\varphi = k\alpha;\ k = \varphi * / \beta;\ \beta = \pi/2 - \alpha_0$$

The parameter k characterizes the constancy of the segment OO_1 from the toe reference point O_1 to the turning point of the hip O and the constancy of the segments $M_3M = M_1M_2 = N_1N_2 = l_2$. As a result, it is this parameter, as it should be in the system with one degree of freedom, that allowed to connect the angles of rotation φ and α in linear dependence $\varphi = \alpha k$ (counting for α is



made counterclockwise along the arc N_3M_2).

Fig. 7. *Kinematic scheme of the 4-link mechanisms matching the anthropometric data of the patients.*

To study the dynamics of the gait process, let's consider another kinematic scheme (Fig. 8)

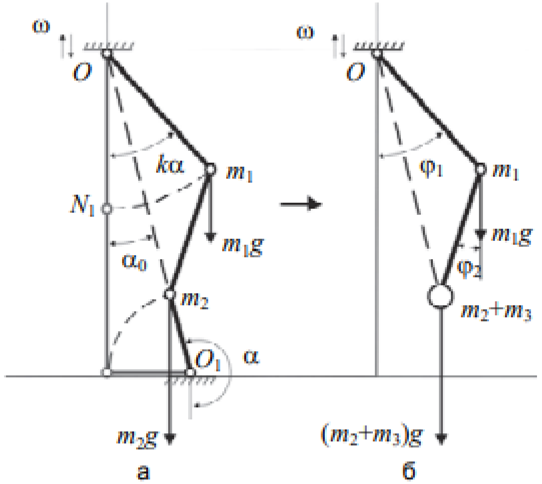


Fig. 8. *Kinematic scheme: with one degree of freedom (a); two degrees of freedom (b).*

Let we focus on the system with one degree of freedom. The dynamics of motion in this case (Fig. 4, a) is described by the equation:
$$\ddot{\alpha} - \frac{m_1 l_1 k \sin(k\alpha) a\omega \cos\omega t}{J} + \frac{g}{J}[m_1 l_1 \cos(k\alpha + \alpha) + m_2 \sin\alpha] = 0,$$

where $J = m_1 l_1^2 k^2 + m_2 r^2$ - reduced moment of inertia; a is the amplitude of the inclinations of the hip joint; m_1 is the mass of the femoral part (ON_1); m_2 is the mass of the tibia (N_1N_2); m_3 is the mass of the foot (N_2O_1); ω is the frequency of oscillation of the hip joint; *g* - gravitational acceleration.

This equation of dynamics, as well as the kinematic scheme and the parameter of contact, presented above, can be used in our case. For example, to control the angles of flexion of the patient's leg in the thigh, knee, foot.

In addition to the mathematical apparatus described in this section, it is necessary to take into account the load applied to the foot of the patient with an increase in the speed of his movement during walking [8]. An example of the dependence of the influence of the load on the part of the patient's body weight with an increase in the tempo of walking is shown in figure 9.

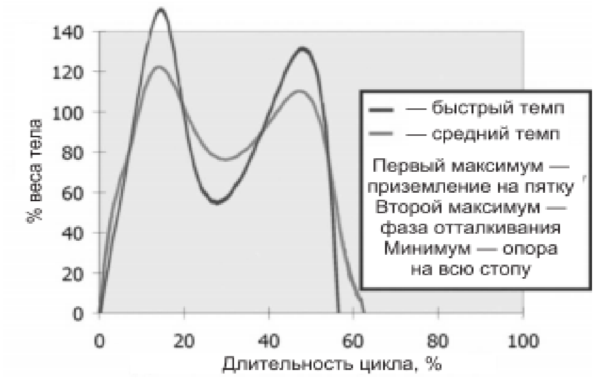


Fig. 9. *Plot of dependence between body weight, step cycle duration and walking tempo.*

On the y-axis is pictured the load as a percentage of the index of the body acting on the parts of the foot parts contacting the floor when walking; on the x-axis the duration of the step cycle is depicted; the graphs for the fast walking is shown in a dark color.

4. Prototype`s Work Correction

A model of the already designed prototype of the restoration of the motor abilities of the human lower limbs was considered in this work. Mathematical models and parameters characterizing conditionally normal gait were presented. After conducting both virtual simulations and real tests of the prototype, it will be possible to find a mathematical model of the movement of the leg. Obviously, if the physical parameters of the mathematical model are noticeably different from those found in the scientific literature, it will be necessary to make major changes to the design of the prototype. Whether any of the parameters is significantly different from the indicative, and the others are normal, or every parameter does not differ much from the indicative parameters, then it will possible to try to make progress by adjusting the already existing variable parameters of the prototype or with small design modifications. For example, if a too large impact load is fixed on the foot during recovery procedures, it will be possible to reduce the speed of rotation of the motor shaft; if the bending angle of the foot is less than the norm – it can be reasonably to try to make the pedal of a more complex shape fixing only the front of the foot or fix the thigh in a certain position or even change the body position relative to the pedals etc.

5. Conclusion

Concluding, it is worth noting that the presented method of studying the work of the prototype, predicting and identifying its necessary improvements seems quite logical, because it allows analyzing the beneficial effects of the future rehabilitation simulator on different muscle groups involved in a person's gait, providing a comprehensive and effective program for restoring the lower limbs motion abilities of a patient undergoing rehabilitation with the help of the mentioned medical complex.

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