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Biomechatronic neurorehabilitation complex – design, models and control

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***Abstract*— A mechatronic system for neurorehabilitation of motion system of the human lower limbs is presented. Moreover, the structure of the complex and its components – feet training device with acupressure effect on feet, half-bed standing frame (verticalizer), lower limbs exoskeleton to operate them in case of loss of mobility or for active workouts are presented. The complex is designed to help patients who have lost the mobility of the lower limbs, or to work with athletes or astronauts on different stages of rehabilitation.**

Key words: biomechatronics, research rehabilitation complex, standing frame, exoskeleton, feet training device, ankle training device, knee training device, PWM control, pneumatic actuator.

I. INTRODUCTION

The ability of search and pressing impact on biologically active zones of a foot, an ankle and limbs, especially the lower ones, gives hope for improvement, and possibility of full recovery after spinal injury of autonomic functions. The connection of these modules with a mechanism of forced movement of musculoskeletal human leg will form the desired biomechatronic trainer, both on the basis of existing biomechanical stimulators with a treadmill, and as a half-bed – verticalizer. The same stimulator can be used for recovery in sports medicine, rehabilitation of astronauts, and in similar applications [1]–[5]. Such complexes are being developed in a number of laboratories of technically developed countries and commercial firms. They are quite sophisticated devices and have manual control. The main types of devices used for stimulation of the lower members of the musculoskeletal system of a human are the stimulants of feet to imitate the acupressure effects, ankle training devices and other joints, standing frames, which are often used by patients with disabilities, injuries and lesions of the spinal cord (these simulators are extremely important to begin the rehabilitation immediately after the injury, and not only to increase the speed of recovery, but also a chance of a full recovery), lower limb exoskeletons. The advanced modern neurophysiological studies show that the task of creating of a device of such a class is extremely urgent.

II. MEDICAL BACKGROUND, CONSTRUCTION REQUIREMENTS

A. The requirements for the construction of training devices

It is obvious that such training complex have strict security requirements, because it is impossible to see the damage caused by the device, in case of the absence of patient sensitivity of the lower extremities. Consequently, fine adjustment and the presence of feedback are needed to use the device. Also it is important to consider the complex kinematics of joints and maximum possibility of joint mobility of the patient. Equally important issue is to maintain the proper patient gait. Unfortunately, for most modern rehabilitation devices, this task is still not fully solved, that's why many people who had rehabilitation on locomotor stimulants have irregular gait (without rotation of the pelvis around the vertical axis of the body), which leads to progressive deformation of the hip joint [6]–[8].

B. The uniqueness of the physiology of patients

The uniqueness of the physiology of patients. When you configure the described devices it is necessary to take into consideration the specific features of anatomy and physiology of each patient. For example, if the patient has a disease, reducing the mobility of the joints, making it impossible for him to move with large amplitude, that demand bending of knees and the active work of hips.

III. REHABILITATION COMPLEX DESCRIPTION

A. Ankle training device

This element of complex is based on medical orthosis, where one degree of freedom in the sagittal plane is realized on the elastic mount to ensure safety and to compensate the misalignment of the degrees of freedom of the orthosis with the real, more complex, and not cylindrical ankle joint of a human. In this case the differences between the physiological characteristics of specific individuals are compensated with different specially designed inserts in the brace. DC motor with worm gear as a drive is used in the joint. Thus, the maximum torque of the cylindrical joint is comparable to the moment, produced during the walk of a healthy person. Robot control is implemented with the use of a modular microcontroller system "Robocon" (development KIAM RAS [9]). The system includes a single-board serial microcomputer PC-104. The system has a position feedback on the corner and can be controlled both from a computer and without it. In this case, the control program is in memory of the controller. The preventing of excessive stress on the joints of human is controlled both programmatically and mechanically, because it is possible to put on the device top and bottom constraints of the rotation angle. Furthermore from excessive force protects the especially developed flexible actuator mounting. Figure 1 shows the basis for clarity stimulator of a foot without fixing inserts for a particular

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patient rehabilitation. Each simulator has a pneumatic foot training device of foot plate which are described below. Ankle training device can be used both in conjunction with the rest of rehabilitation devices, and separately for the treatment of some diseases or for training.

Fig. 1: Ankle training device

Fig. 1 shows the device in a mobile autonomous version. Control system – all power electro and pneumatic modules and electronic control modules in the block are located next to the training device.

B. Foot training device

The device (Fig. 2) is designed for pacing rehabilitation and prevention of pathologies of the musculoskeletal system associated with diseases that led to the paralysis of the lower limbs. Stimulator provides the mechanical imitation of supporting load, that start the synergistic interaction of motor reflexes ([**?**]–[**?**]).

The principle of stimulator operation is based on the pneumatic pressure on the appropriate zone, there are three of such zones for each foot, which simulates a real human walking. The pressure with the use of special air cameras is realized. Which are controlled by the pulse width modulation (PWM), it is gives one the opportunity to perform any prescribed function of pressure up to a impact (imitation jump). In comparison to the other devices of this type of Russian-made stimulant support zones of the foot, this one has three cameras (one for each area of the foot: heel, arch and metatarsal area), that helps to create more accurate simulation of the process of human walking. The control unit of the device is also based on the modular microcontroller system "Robocon" which was mentioned above, that allows one work with an artificial foot and ankle in the simulator complex, using a single interface. For the safety of patients the module includes the following system: "pressure regulator $\leftrightarrow$ the relief valve" – which provides a safe pressure on the foot of a man.

Another feature of this system is that the stimulator can feed from the standard voltage of 12 V, and as a compressor one can use the electric pump (e.g., automotive), which makes the module very mobile and therefore it can significantly accelerate the clinical rehabilitation of a patient.

Fig. 2: Foot training device

C. Standing frame

In order to begin the process of the rehabilitation as fast as possible, one can use the spinal simulator-verticalizer. This simulator has a construction of a bed and has a modular scheme. The adjustible mountings are installed and handles to support a patient. The simulator can be easily disassembled and placed into the luggage compartment of the car, so it can be used not only in hospitals but also in other conditions (e.g., mobile applications).

The complex also includes a lower limb exoskeleton. Fig. 3 shows half-bed with a dummy and an exoskeleton. There are currently three degrees of freedom of half-bed - two of them are controlled and one is passive - the turn of body around the vertical axis. Lifting power is controlled by an electric motor and has a feedback on the corner. Also this degree is used when developing the simulation of movements squats, etc. The second degree turns patient's body around a horizontal axis perpendicular to the inclined axis.

Fig. 3: Standing frame

With this design, the kinematics of motion of pelvis is realized. In the future, all three angular degrees of rotation of the pelvis will be active. The control unit of all rehabilitation complex is mounted on the housing of the half-bed verticalizer.

D. Lower limb exoskeleton

To simulate human walk and development of human lower limb the exoskeleton is created. This exoskeleton design has significant differences between foreign and native ones [13], [14] since the system does not have its own joints, which imitate or follow human joints. Due to this, the problem is solved by an exact repetition of the kinematics of the particular patient, moreover, by software. Exoskeleton has a modular design, and some joints can be easily added or removed to create a more rigid or flat design. The basic assembly exoskeleton consists of five hard parts - seat, attachments to the leg and thigh, interconnected cylinders. Most pneumatic cylinders are attached to the rigid parts of assembly using two- or threefold hinges. So, the structure may have six degrees of freedom of the hip mounting related to the seat and six degrees of freedom of the thigh mount related to the hip and seat. Thus, in this assembly arbitrary human foot movements can be realized, which are limited only by the moves of cylinders. On the first stage of practicing movements small diameter cylinders are used on a mannequin to ensure safe working with the pressure of 8 bar. Cylinders also are easily replaced with both, similar to the other type of work, and cylinders of different diameter, which allow to adapt the design for a particular patient easily and quickly.

Fig. 4: Lower limb exoskeleton 3D model

Fig. 4 shows the form of the exoskeleton mounted on a half-bed simulator to imitate squatting. In this assembly the device has eight controlled pneumatic cylinders, the other degrees of freedom remain passive, so as not to do harm to human gait. The cylinder has a magnet, so it is possible to realize the feedback using the Hall sensors. Each of the eight cylinders is controlled by two normally-closed valve in a pulse width modulation at frequencies close to 50 Hz.

IV. SYNTHESIS OF COMPLEX CONTROL

The technique of control of complex modules is shown as an example on the exoskeleton, as this module requires the most sophisticated control. The current version of the main drives of module are pneumatic, produced by Pneumax, Italy (see [15]). Full cycle of the exoskeleton consists of several phases, the main ones are following two: the walking pattern construction and the performance of this pattern by the pneumodrives of module.

A. Synthesis of the walking pattern

The first phase demands to perform a motion scheme of the limbs. Walking pattern for the exoskeleton can be built in different ways. We use motion capture system made for recording and processing of natural human walking. Computer vision algorithms solves the problem of filtering image noise, combining information from different cameras, detection of body parts, as well as determining the position and orientation of parts of the body during movement. This part of the implemented by markerless motion capture system by iPi Soft company iPi Recorder and iPi Mocap Studio. We use pair of Microsoft Kinect as sensors.

The output is a file with the structure of the multilink model in BVH file format. BVH format widely used as motion capture data representaion.

The model chosen conditional center - solid (conditionally human pelvis), for which recorded it's position in space x, y, z and rotation α, β, γ in fixed coordinate system relative depending on the time. The configuration of each unit is described by three angles of rotation units α_i, β_i, γ_i relative to the previous node. That is attached to the pelvis and torso two thighs, so their position is determined by three angles of rotation about the axes rigidly attached to the pelvis. Similarly to the thighs attached shin and foot to them.

Having such data for all required units over time, we get the full law of motion model.

Some motions were captured during experiments. In this work we deal with one of them. See figure 5.

Source data contains a small measurement noise, which in the calculation of the second derivative turns into noise of significant amplitude. We use convolution of input with Hanning window function for processing data.

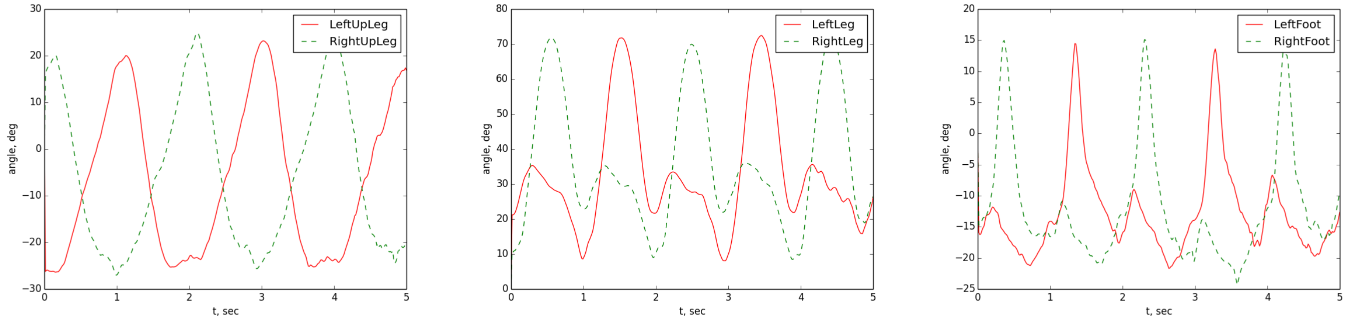
$$\omega(n) = \frac{1}{2}\left[1 - \cos\left(\frac{2\pi n}{N-1}\right)\right]$$

Another option is to build trajectories on chosen points of limbs according to the physiological data [16]. One should notice that it is very approximate, but still this option gives a general picture of the motion with reasonable accuracy.

B. Testing of the walking pattern in the complex

After the typical trajectories of pattern and the laws of motion of the representative points on them are built, they are performed as the laws of motion of the drive cylinder unit. This conversion can be done on the basis of cyclic calculation of the inverse kinematic problem (IKP) for the exoskeleton, which is not a trivial one because of the redundancy and complexity of its kinematic scheme.

For a complete calculation, for IKP and for the inverse dynamic problem (IDP) to control the force, exerted by clamping cylinders, full dynamic model of a complex software package "Universal Mechanism" (Universal Mechanism)



(a) Thigh (b) Shin (c) Foots

Fig. 5: Law of motion

combined with means package Matlab SIMULINK [17], [18] is realized. Fig. 6 illustrates one of the stepping cycles of the exoskeleton. As the stepping cycle is considered an ellipse following form:

$$\begin{cases} x = x_0 + a\cos(T_0 t), \\ y = y_0 + b\sin(T_0 t). \end{cases} \quad (1)$$

Here x_0, y_0 – center of the ellipse in the coordinate system associated with the seat of the exoskeleton, $2a$ – step length, $2b$ – step height, T_0 – parameter that specifies the time of one stepping cycle.

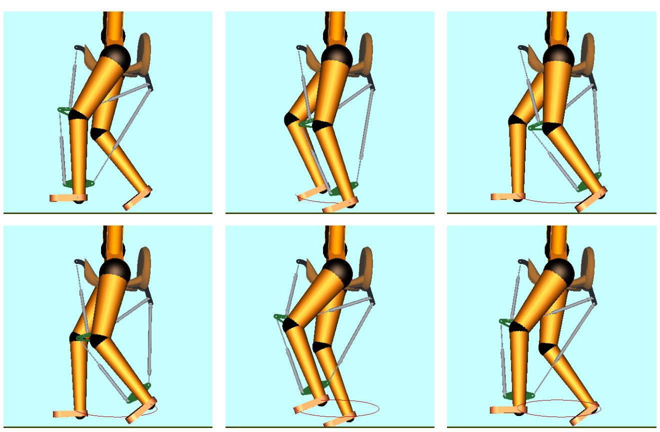


Fig. 6: Stepping cycle storyboard for the exoskeleton

Below in Fig. 7–9 the connection of time and various system parameters is given (modeling results in Universal Mechanism): angular connections in the hip and knee of the left leg, connections between the time and the length of the cylinder of the exoskeleton's left leg, speed of cylinder rods of the exoskeleton's left leg – for the following parameters of a stepping cycle: $2a = 0.4m$, $2b = 0.08m$, $T_0 = 2$. The inverse problem of dynamics (Fig. 10) can also be solved in Universal Mechanism.

Resulting trajectory motion of cylinders in the modular microcontroller system "Robocon" is implemented. This system has a complete library of the lower level to control

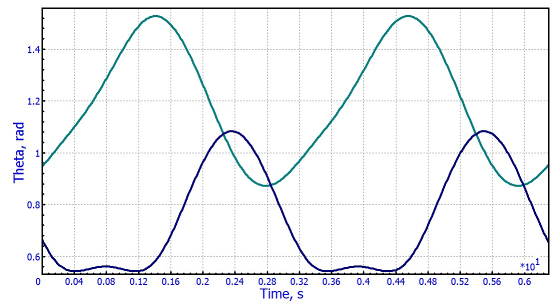


Fig. 7: Angular dependence of the time in the hip and knee joints of the left leg

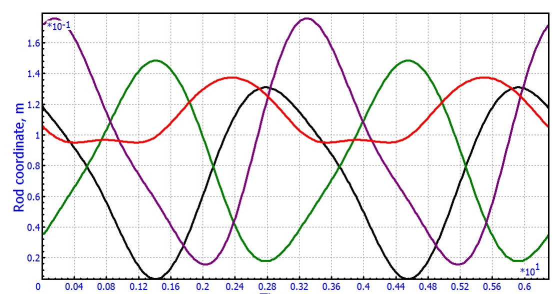


Fig. 8: Joint trajectory of the pneumatic cylinder

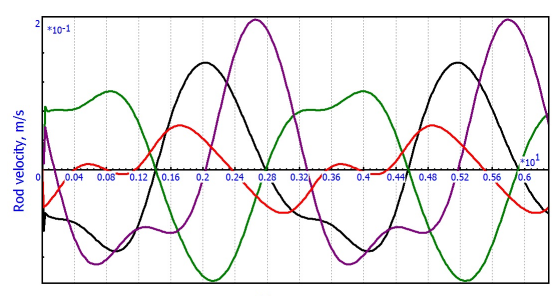


Fig. 9: Velocity of the exoskeleton cylinder rods for the left leg

the drives and to input the analog or digital sensors. Top-level programs are executed on an external computer, which control the complex and displays the received telemetry.

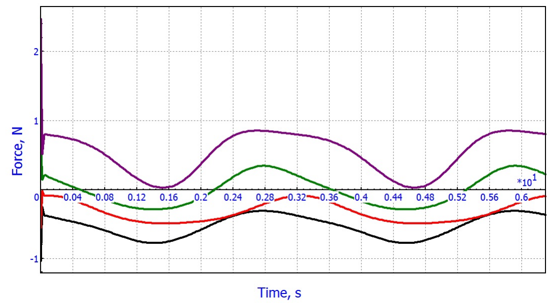


Fig. 10: Inverse dynamics

V. CONCLUSIONS

It was developed the system of software trajectory control of the rehabilitation trainer of lower extremities (exoskeleton) on the basis of the analytical solution of the inverse kinematics problem for this machine.The experiments were performed in the software package "Universal Mechanism", it was received the connection between power and time, which appear in pneumatic cylinders as a result of working out the desired path. Control system based on computer modeling was developed for the implementation of stepping patterns in a rehabilitation simulator for the lower extremities of a person. As a trajectory of a point of a person's ankle one selects the arc of an ellipse, which approximate the phase of a step and the section corresponding to a phase when it touches surface. In the software package "Universal Mechanism" obtained the connection between $l_k(t)$ – law the length of the pneumatic cylinders and time. The resulting functions are realized with the help of PWM-control on pneumatic valves. The determining technique of trajectory of an ankle's point on the device is developed. The system is based on a visual inspection of the markers and on computer analyzes of the images received from the camera. The same system is used to adjust the trajectory during system's settings for the rehabilitation of the individual patient. Thus, the complex does not require any mechanical adjustment for a particular patient (in case it is possible to conduct the above-described algorithm in advance). It was reworked the mechanics of the rehabilitation complex to increase the smoothness of motion when working out trajectories. It was designed and manufactured the electronic part of the control circuit. A system of interaction of complex with computer is built, moreover, software was developed to realize the control.The experiments which we conducted with the help of this complex showed its success and value. Due to numerical and analytical models the control laws can be deduced effectively. Figure 11 below shows the storyboard several phases of the exoskeleton with a dummy person in a real experiment on the complex. First experiments showed that the PWM-control pneumatic valves gives a trajectory error of 10-20 %.

Fig. 11: Storyboard for some stepping phases of the exoskeleton

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