Development of a biomechanical robotic orthopedic apparatus with a corset based on composite materials

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Abstract. The article presents the results of a comprehensive study on the creation of a biomechanically based robotic orthopedic apparatus (ROA) with a lack of functionality for limb removal. A number of biomechanical schemes of the biotechnological system "man-ROA" have been developed, as well as a control system for the motor functions of ROA. Electromyographic signals were chosen as controllers. A microprocessor control system has been developed. The typical actions of the ROA user are defined. The software of a neuro-controlled node has been developed. Design, manufacture and debugging of a neuro-controlled unit and ROA in general was completed. The use of composite materials made it possible to improve the biomechanical characteristics of walking and reduce the energy consumption of the entire biotechnological system.

1. Introduction

The problems of efficient reproduction of human locomotion and, above all, walking with the help of mechanical devices such as orthopedic devices in patients with disorders of the musculoskeletal system have a deep history. Beginning in the middle of the 20th century, when interest in the problems of movement efficiency increased, questions arose and definitions of the energy efficiency of walking of two-legged walking devices. In particular, in [1, 2], with parametric optimization of movement models by the criterion of energy consumption, it was determined that walking anthropomorphism is of great importance. Attention is also paid to reducing energy consumption during rational oscillatory movements of the body and limb. In this case, the moments of force in the joint, providing the movement of the links of the model, are significantly reduced. It was noted that optimization of walking speed has a big impact.

Mathematical modeling of two-legged walking conducted by V.V. Beletsky [1,2] showed that the so-called “comfortable” movement, when the center of mass moves linearly, is significantly less energetically beneficial than uncomfortable movement, when there is a movement of the center of mass similar to anthropomorphic walking, characterized by rocking movements of both the trunk and legs. In
this case, the required energy costs are almost halved. The simulation showed that the use of passive springs as energy storage is rational and energetically beneficial. This confirms the need for energy recovery when walking with the help of elastic elements.

Based on these works, it can be concluded that anthropomorphic movements during locomotion are carried out by more than 60% due to the rationality of biomechanical characteristics and only less than 40% due to the direct action of the moments of force in the joints. Walking is more economical, the less connections are imposed on it. For each connection made, you have to pay extra energy to maintain this connection.

Thus, it is advisable to achieve a reduction in energy consumption for movement when walking anthropomorphic mechanisms due to rational vibrational movements of links having a certain mass, optimal impulse application of torque in joints and integration of elastic elements for certain parameters of legs and speed.

Such conclusions served in the future as the basis for conducting mathematical modeling and studying the influence of the parameters of prosthetic and orthopedic products on the biomechanical characteristics of walking. The results of these studies are presented, including in [3,4,5].

A comprehensive analysis of the results of these studies made it possible to take a fresh look at the influence of biomechanical characteristics on walking support, which found its application in this work.

Of particular importance, these biomechanical characteristics become necessary when it is necessary to restore the functions of the lower limb partially lost as a result of various diseases and deformations of an orthopedic nature. In this case, a combination of “living” and “non-living” appears, segments, links, and joints.

Consider the case when one of the lower limbs is affected in combination with lesions of the spine in the lumbar region, which is widespread in a number of diseases and deformities. In addition, similar orthopedic pathologies of the lower limbs can be caused by a number of neurological diseases.

In this case, flaccid paresis, paralysis of various degrees of manifestation, accompanied by pathological settings, contractures in the joints of the lower extremities, secondary deformations appear. The greatest loss of walking opportunities is manifested in case of muscle damage in the hip joint, when it is difficult to push the lower limb into the phase of the back push and carry it forward to the phase of transfer. In some cases, flaccid paralysis is combined with spasticity of individual muscles of the lower extremities. As a result, the patient has difficulty and limited movements necessary for walking, delay, lack of skills that provide locomotion.

Consider which muscles carry out movements in large joints of the lower limb, as well as the movement of the spine, which was one of the objectives of this work. This allowed us to further determine the most rational places for the installation of sensors and was used in the design of the corset.

Of greatest interest are movements in the hip joint. Hip joint flexion mainly involves the iliopsoas, sartorius, muscle tensioner of the wide fascia, scallop, and thigh muscle. The extension involves the gluteus maximus, biceps femoris, semitendinosus, semi-membranous, large conductive.

We also indicate the muscles that perform certain movements of the spine. During extension v trapezius, posterior dentate muscles, upper and lower plaster muscles of the neck and head, cruciate, transverse, short muscles of the back (transverse, interspinous, lifts of the ribs and the group of the occipital-iliac muscles).

When bending - sternocleidomastoid, scalene, long muscle of the head and neck, rectus abdominis, oblique abdominal muscle, iliac lumbar.

In severe cases, as a rule, with the consequences of spinal injuries accompanied by spinal cord injury – a combination of a back injury and spinal cord injury to the spinal cord, the motor functions of both lower extremities are affected. In these cases, medical exoskeletons are currently used. But in cases of moderate severity or relatively uncomplicated cases, in the above series of diseases and deformities, when one limb is affected, their use is not advisable from a medical, biomechanical or economic point of view. In [6], the view was expressed that the widespread introduction of exoskeleton requires discussion and the work of an interdisciplinary team.
Well-known medical exoskeletons do not give to the patient himself to participate properly in the process of locomotion, to use the biomechanical characteristics inherent in man to ensure movement in conjunction with the device. Such patients partially retained motor functions, that is, they have mild, moderate degrees of damage, with lesions localized mainly at the level of the hip joint in combination with lesions of the spine at the level of the pelvic and lower thoracic spine.

For most diseases and deformities, the consequences of which are paresis and paralysis, these exoskeletons cannot be used, since in addition to activating motor functions, the main therapeutic factor is the provision of orthopedic correction of the limb, which is absent in them. Most exoskeletons cover both legs and several joints, and not one of the most affected or on which the walking process depends more. On one joint, the use of exoskeleton is very rare. For example, its use on the ankle joint is known [7].

Also, as a rule, elastic elements are not built into medical exoskeletons, they do not have a rational use of mass-inertial characteristics, and they do not take into account the possibility of the influence of the construction scheme on the normalization of biomechanical characteristics. The operation of many types of medical exoskeleton requires an operator accompanying the patient.

Instead of exoskeleton, it is more rational to limit oneself to the use of biomechanically sound orthopedic devices. However, their designs must combine:

– rational kinematic construction scheme;
– rational mass inertial characteristics;
– built-in elastic elements;
– devices that reproduce motor functions due to built-in drives and an external energy source.

Existing traditional orthopedic devices do not fully meet biomechanical requirements. In addition, indications for their appointment are limited due to a number of inherent disadvantages. Including they have a large mass and are not convenient enough to use. As for the ability to reproduce motor functions that complement the residual muscle capabilities, they are absent in known orthopedic devices.

2. Biomechanical scheme of a robotic orthopedic apparatus

We conducted a comprehensive study on the creation of a biomechanically grounded robotic orthopedic apparatus (ROA) for people with disabilities and patients with lesions of the lower limb and lower torso who have a lack of functionality to carry the limb into the transfer phase. Such a removal is normally carried out due to the action of muscle forces on flexion in the hip joint at the beginning and middle of the transfer phase and the action of muscle forces on extension at the end of the transfer phase until the start of the front push. In this period, the mass inertial characteristics of the limb, which provide the pendulum motion, and the location of the rotation axes of the joints, and the potential energy accumulated due to the elastic properties of the ligaments, muscles, and tendons, passing into the kinetic at the moment the limb is torn off, simultaneously affect the limb.

A number of biomechanical schemes of the biotechnological system "man-ROA" have been developed. So, to determine the effect of the mismatch of the hinge axes with the axes in the joints, a developed biomechanical scheme is proposed that combines the links of the orthopedic apparatus with segments of the lower limb and its analysis is carried out. In orthopedic devices on the lower limb, the projections of the hinge axes on the sagittal plane, as a rule, do not coincide with the projections of the axes of the corresponding joints of the orthopedic device. This is due to both the absence of knee nodes providing rotation of the hinge along the hypocycloid, which is characteristic of the movements of the knee joint, and the need to create under-stability in the knee joint when walking, as well as a number of clinical indications. Errors arising during the assembly of the orthopedic apparatus also lead to mismatch of the axes.

The difference in the location of the axes of the joints of the orthopedic apparatus and joints of the limb causes when walking the displacement of the links of the apparatus relative to segments of the limb. This leads to piston-like movements of the limb in the sleeves, causes a change in the load on various areas of the limb, affects the functional length of the limb in the biomechanical "man-orthosis" system and the provision of movements in the joints. Therefore, it was considered advisable to consider
in more detail the effect of the mismatch between the axes of the hinges of the orthopedic apparatus and the joints of the limb on the biomechanical system, and based on the analysis of this problem, develop some recommendations that can be used in the assembly and creation of designs of ROA.

As a result, the optimal location of the hinges relative to the joints of the limb was revealed, both from the standpoint of under-stability, and from the point of view of changing longitude dimensions in the biokinematic chain.

The masses of links combining the masses of segments of the affected limb and the mass of sections of ROA located between the joints are selected. Moreover, the use of the original composite material sleeves as materials made it possible not only to lighten the ROA mass, but also to regulate the mass-inertial characteristics by providing oscillatory movements of the tibia links with the foot, bringing them closer to normal.

In addition, the use of composite material allowed the construction of the sole of the ROA foot sleeve in the form of a spring. This, in turn, made it possible to enhance the repulsion of the distal ROA with the limb installed in it in the phase of the back push, thereby improving the biomechanical characteristics of walking and reducing the energy consumption of the entire biotechnological system. In addition, ROA uses elastic polymeric four-leafed ankle joints, and an elastic element is installed in the hip joint, which is compressed during re-extension in the sagittal plane in the hip joint from the vertical posteriorly at the end of the foot support phase. At the very beginning of the transfer phase, the elastic element is unclenched, and the accumulated potential energy passes into the kinetic energy, developing a moment of forces that contributes to the removal of the apparatus with the limb in the sagittal plane. The appearance of the ROA frame is shown in figure 1.

![ROA frame made of composite material.](image)

3. The control system for the motor functions of ROA
Particular attention in this work was paid to the study of the ROA motor function control system and the selection of its most rational option. Known control systems used in lower limb prostheses, medical exoskeletons, usually assume control programmed depending on the signals of pressure sensors located under their plantar surface or on myotonic signals of limb sections, as well as movement programs similar to the norm taking into account pathology. As for the control from electroencephalographic
signals, as noted [8], the development of brain-computer interfaces for controlling movements of the lower limbs using imaginary leg movements is complicated in that the data analysis procedure must take into account a large number of artifacts in the recorded EEG signals caused by electronics executive mechanisms of movement, intense body movements and tonic muscle activity.

Our analysis showed that it is advisable to use electromyographic signals as control signals, which confirms the conclusions made in [7]. However, when developing motor functions from an external energy source relative to the hip joint, it is advisable to combine electromyographic signals with the signals of pressure sensors under the sole of the ROA foot sleeve, which was not previously used.

The developed microprocessor control system for ROA with an external energy source (EES) provides the implementation of a sensor feedback system, setting up settings and work patterns using a local user myointerface.

In this case, for control, bioelectric signals obtained from the skin electromyographic electrodes from the muscles of the trunk and pelvic region, depending on their safety and activity, were used.

In order to develop a preliminary design of a neuro-controlled node, its structural scheme was developed and the components included in its composition were selected.

The main components of the neuro-managed node are:
- control board with a microcontroller;
- drive system of the push mechanism;
- control sensors;
- sensors and feedback sensors;
- elements of a local control system;
- an external source of energy.

It is assumed that in a neural-controlled node fed by an external energy source, using the elements of the local control system, the user will select the operating mode of this neuro-controlled node.

At the same time, depending on the selected operating mode, when a signal is received from the control sensors, the microcontroller of the control board will transmit control commands to the drive system of the jog mechanism.

The position of the jog mechanism, in turn, will be determined and corrected by the microcontroller based on the signal of the sensors and feedback sensors.

The main component of the neuro-controlled node, which mechanically provides bending and extension of the hinge joint of the biomechanical robotic orthopedic apparatus, is the drive system of the push mechanism.

Initially, a worm gear motor was considered as a drive for the jog mechanism.

However, despite its advantages of a constant torque, the drive of the jog mechanism based on a worm gear motor would require its installation directly in the hip joint, which would significantly increase the external dimensions of this joint and exclude the possibility of using standard joints offered by the industry.

In this regard, a linear actuator with a DC collector motor was chosen as the drive of the jog mechanism.

To provide feedback on the position of the linear actuator rod, options for using a potentiometer and incremental encoder were considered as feedback sensors.

Although the potentiometer provides an absolute value of the position of the actuator rod, proportional to the change in the electrical resistance of the potentiometer, its use significantly increases the longitudinal overall dimension of the actuator.

Therefore, an incremental quadrature encoder mounted on the shaft of the actuator motor was selected as a feedback sensor.

Due to the stable discharge characteristics and high specific energy intensity, a lithium-iron-phosphate storage battery is selected as an external energy source.

To select a control board with a microcontroller, we analyzed the characteristics of several debug boards that are most suitable for solving the required control tasks.
According to the results of the analysis, a board based on the Atmel ATmega 328 microcontroller is selected as a control board with a microcontroller.

The capabilities of the control board did not allow direct connection of the jog mechanism drive, therefore, for direct drive, a high-power motor controller was introduced into the structural diagram of the neuro-controlled unit.

For additional control of the operation of the drive system of the jog mechanism, a current sensor is used installed on the power line of the motor controller.

Two laid on active electromyographic electrodes, which should be fixed on top of the user's control muscles to capture their bioelectric signal, are selected as sensors for controlling a neuro-controlled node.

Of the electromyographic electrodes produced by the industry, the electrodes produced by SPE “Galateya” corresponded most fully to the solution of control problems.

To improve the quality of control of a neuro-controlled node, two corrective pressure sensors, which are supposed to be placed in the forefoot and heel of the artificial foot of a biomechanical robotic orthopedic apparatus, are additionally added to the structural diagram.

Two versions of these control pressure sensors are proposed.

In one design they are push limit switches, in the other they are film load resistors.

To implement a local control system for a neuro-controlled node, the typical actions of a user of a biomechanical robotic orthopedic apparatus are determined.

Two versions of these control pressure sensors are proposed.

In one design they are push limit switches, in the other they are film load resistors.

To develop the software of a neuro-controlled node, the algorithms of its operation are determined when performing basic actions in the three modes described above.

When you turn on a neuro-managed node, its initialization is performed. At the same time, the values of the pre-set constants of the settings of the sensors and the time parameters of the node’s operation are loaded into the microcontroller’s memory. The drive of the push mechanism with control of the current strength and the position of the rod is displayed in the starting position of the walking mode.

Then begins the cyclic execution of the main block of the control program. In this case, the signals are read from the operation mode switching buttons, the potentiometer for setting the speed of the jog mechanism drive, as well as from the first control electromyographic electrode and pressure sensor located in the toe of the biomechanical robotic orthopedic apparatus.

If the values of the signals from the first control electromyographic electrode and the pressure sensor located in the toe of the biomechanical robotic orthopedic apparatus exceed the values of the respective settings, the first phase of the step begins.

In this case, the drive of the push mechanism starts bending the hip joint with control of the current strength, position of the rod, time and signals from the second control electromyographic electrode and pressure sensor located in the heel of the biomechanical robotic orthopedic apparatus.

If the signal values are exceeded from the first control electromyographic electrode and the pressure sensor located in the toe of the biomechanical robotic orthopedic apparatus of the corresponding setting, the first phase of the step begins. Otherwise, at the end of the second phase of the step, the neuromodule awaits the initiating signal to execute the first phase.
Figure 2. Schematic diagram of a neuro-controlled ROA node.

When the operating mode is switched to the "sit down" mode, the drive of the push mechanism starts bending the hip joint to an angle of 90 degrees with control of the current strength, position of the rod, and time.
When the operating mode is switched to the “stand up” mode, the drive of the jogging mechanism begins to extend the hip joint to the starting position of the walking mode with control of the current strength, position of the rod, time.

To return to walking mode, the user must press the appropriate button.

In order to debug a manufactured prototype of a neuro-controlled assembly, the drive of its push mechanism was fixed on the design model of a biomechanical robotic orthopedic apparatus made on the basis of the scientific and production laboratory of orthoses of OOO «Orthopedic Small Enterprise «ORTEZ».

During debugging, the values of the constants of the sensors operation settings and the time parameters of the node operation were adjusted. As a result of debugging, the operation of the neuro-controlled node is ensured in the planned mode.

Based on the conducted research, the design and manufacture of ROA was performed.

4. Conclusion

The developed ROA provides:

– controlled translational-translational movements of the thigh segment into the phase of transfer of the lower limb, initiated by bioelectric signals and carried out by a neuro-controlled node;
– the implementation of orthopedic correction, fixation, unloading of the affected limb;
– improvement of elastic, kinematic, mass-inertial biomechanical characteristics of ROA;
– minimization of cosmetic damage;
– the presence of an elastic element in the hip node;
– both walking and patient sitting on a chair, stool, etc.

At the same time, in ROA with EES it will be necessary to carry out:

– energy recovery due to elastic elements;
– the implementation of the front plantar region of the sleeve of the foot in the form of a spring, which will allow the patient to reduce energy consumption for movement, reduce energy consumption of renewable energy sources and the weight of the wire;
– rational distribution of the load on the affected limb due to the manufacture of individual sleeves of the foot, lower leg, thigh;
– creating orthopedic correction and reducing the likelihood of secondary deformations, increased comfort;
– reducing the effects of piston movements and thereby reducing trauma to the skin, circulatory disorders;
– a rational kinematic construction scheme, providing under-stability in the knee joint when walking;
– a decrease in the mass of ROA in comparison with traditional ones;
– the possibility of thermoforming of thermowells as medical indications and anthropometric parameters change, carried out at a temperature of less than 90°C.

Thus, the studies and design developments made it possible for the first time to develop a system of bioelectric control of the motor functions of the hip joint of a robotic orthopedic apparatus. An integrated approach to the design of ROA from the standpoint of biomechanics has improved walking characteristics and reduced energy consumption; the mass of the battery, drive ROA.

The results of the work performed allow us to talk about the prospects of the selected direction of rehabilitation of disabled people and patients with injuries of the musculoskeletal system and the need for further research and practical application of ROA.

The cluster approach, which brought together specialists from organizations of various fields of activity, made it possible to carry out a comprehensive review of multidisciplinary problems “at the intersection of sciences” and find promising solutions in research and the creation of innovative prosthetic and orthopedic products.

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