Exoskeleton as a New Means in Habilitation and Rehabilitation of Invalids (Review)

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The problem of development and implementation of exoskeletons has been analyzed on the basis of the Russian and foreign literature. Military Industry and rehabilitation medicine are shown to be currently the priority fields of exoskeleton application. It has been noted, that the majority of the existing exoskeletons cannot be widely used for the rehabilitation of the patients with limited functions of the upper and lower limbs because they are heavy, external power supply-dependent, and expensive. Two types of exoskeletons, active and passive, have been considered. The design of the passive exoskeleton is shown to be most acceptable for use. The analysis has revealed, that the main groups requiring exoskeletons, include patients suffering from paresis of the upper and lower limbs.

Key words: passive exoskeleton; active exoskeleton; paresis; invalid.

Exoskeleton (from the Greek ἔξω — external and σκελετος — skeleton) is a device, designed to boost the human strength by the external framework [1, 2].

There exist exoskeleton models with active and passive principle of action: active and passive exoskeletons. Active models use external units as a power source, whereas the mechanics of the passive exoskeletons relies on the kinetic energy and a human strength.

Active exoskeletons found a wide application in the Armed Forces, however, the secrecy of their development made the analysis of their design impossible. The majority of such developments belong to the Pentagon. One of the known exoskeletons, *HULC* (Lockheed Martin, USA) allows the soldier to move quickly with a heavy load over a rugged terrain. The HULC helps not only transfer the load, but to lift it from the ground. The device weight is 25 kg, batteries making the main part of the load. The batteries can keep HULC operative for 2 h. The exoskeleton design enables soldiers to carry an extra 25 kg of ammunition. The operation of the device is limited by climatic conditions, i.e. high or low temperature. Maintenance of the HULC may be done by the specialists only [3, 4].

XOS (Sarcos, USA) represents a specialized suit designed for the warfighters of the ground units. Its main drawback is constant connection with the power supply. Its weight, 70 kg, also limits its use [5–7]. Both described exoskeletons are designed to enhance durability, and strength of lower and upper limbs in healthy people, such as military men.

In a number of countries the development of active exoskeletons is the subject of social projects. Their task is the compensation for the lost functions and physical and social rehabilitation of the patients. Examples are exoskeletons ReWalk, REX, HAL, eLEGS, which constructive features aim to help people with difficulties in moving.

ReWalk (ARGO Medical Technologies, Israel) enables people with paralysis of the lower part of the body (paraplegia) to walk resting on the sticks. The work of the system is based on the sensors, detecting the body bending forward and transmitting the signal to the devices supporting the legs. The cost of the apparatus is $100,000. It is powered by the batteries, located in the special backpack. The apparatus can be used only by the people with the preserved functions of the upper limbs [8–10].

REX (REX Bionics, New Zealand) provides complementary spatial support to the human body while moving. Control is made using a joystick and control

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pad. The exoskeleton is 38 kg, which together with a high cost, $150,000, makes it unaffordable for a wide application [11].

HAL (Hybrid Assistive Limb, Cyberdyne, Japan) is intended for the elderly and invalids with mobility disorders. The total device weight is 23 kg, height 160 cm. Besides, accumulator battery weighs 10 kg, and provides 2.5-hours of active use on a full charge at a maximum load condition. The device costs $4200 [12].

eLEGS (Esko Bionics, USA) is a special hydraulic exoskeleton, designed for patients with partial paralysis of the low limbs. The device enables them to move with the help of crutches or special walkers. A gesture-based hardware-software interface complex uses natural human movements, translating them safely to the action of the exoskeleton through the microcomputer [13, 14].

An example of an active upper body exoskeleton is a fragment of an upper limb *Titan Arm*, designed by the engineering students at the University of Pennsylvania. The construction is compact, inexpensive in production (exoskeleton elements are made by a 3D-printer). The system is powered by the batteries which are attached to the back, and activated via cables and cords. Constructive features of this project are under patent protection, and engineering drawings are not presented [15, 16].

Passive exoskeletons found their applications mainly in the military purposes.

In Russia, Transport Walking Systems company created a passive *exoskeleton K-2*, designed for military and emergency needs [17]. This device helps a man to carry heavy loads (backpacks, body armor, sapper protection kits, fireman outfit) weighing up to 50 kg for a long time without great strength and load on his own musculoskeletal apparatus. Minimal dimensions and weight (from 2 kg), ergonomics, and simplicity in service make the device indispensible aid in long-term expeditions, forced marches, in the regions of emergency situations. The exoskeleton is mainly made of carbon fibre, giving the device a high durability and low weight. The exoskeleton can be also used in musculoskeletal system injuries, enabling a man to move over large distances with the damaged lower limb, including fractures, by fixing it additionally to K-2 device with a gauze bandage or straps upper or lower the lesion. Exoskeleton K-2 provides complementary protection of lower limbs and spinal column from mechanical injuries. The designers of this system note the feasibility of its application for invalids with lower limb function disorders.

A group of Russian scientists at the Scientific Research Institute of Mechanics, Lomonosov Moscow State University, designed a working prototype of passive exoskeleton *ExoAtlet P*, intended for the soldiers and rescuers, allowing the wearer to carry heavy loads (70–100 kg). A modification of this exoskeleton, ExoAtlet P-1, was created to relieve the load from the fighters while transferring assault shields. This exoskeleton model is equipped with the unit for fixation and fast taking off the shield, which is important in combat operations. Application of the system is indicated in the following situations [18–22]:

removal of rubble in emergency and rescue works and elimination of the consequences of natural disasters or technogenic catastrophes, firefighting with the limited air volume in the breathing apparatuses;

building construction and for the tasks, connected with carrying heavy loads over long distances;

mine clearing and counter terrorist activity;

assistance to people with physical disabilities and transporting bed patients: patients obtain the ability to walk, go up- and downstairs, sit down and stand up without any help.

The apparatus ExoAtlet P is thought to be a man-machine symbiosis with mechano tactile interaction. It is an integration of a man and a robot [18].

We found the following descriptions of passive exoskeletons in the foreign literature.

A soft pneumatic exoskeleton was created by the team of researchers from Carnegie Mellon University, Harvard University, University of South Carolina, Massachusetts Institute of Technology and wearable sensor developer Bioscience. It houses flexible artificial muscles, lightweight sensors and control software. The device is made of a soft elastic polymer.

At present, it can be worn only on the low leg, the biological structure of which is diligently replicated in the device. Three cylindrical artificial muscles correspond to the muscles of the anterior and one to the posterior part of the leg. Artificial tendons (steel cables) extend from the ends of these muscles downward to the foot and serve to move the ankle.

A feedback is provided by hyperelastic strain sensors, located on the top and lateral part of the ankle. Every sensor consists of the rubber sheet, containing microchannels, filled with liquid metal-alloy conductor. The shape of these channels changes when the elastic material stretches or compresses, altering electric resistance of the metal. Once the change of the resistance is registered, the software can ascertain the position of the ankle joint.

The mobility is provided by flexible materials, but flexibility poses a certain problem: it is more difficult to control the device than the exoskeleton made of the usual rigid materials, therefore sensors must be more sensitive and the control more precise. Laboratory tests showed, that this device is able to move the ankles of the examined people within a 27-degree range of motion, which is considered sufficient enough for the normal walking gait. But this is only a prototype, and at present scientists are on the way of improving the construction to make it more convenient for the patients with movement disabilities [23–25].

Exoskeletons of this type reduce matabolic rate, which usually rises while walking, and therefore these devices are successfully used to teach people walking and restore the lost functions in post-stroke patients and in those who need rehabilitation after cerebrospinal traumas [28–32].

An experimental model of the upper limb exoskeleton *Exoskeleton Prototype 3* (EXO-UL3, University of California, USA) owing to the drives, controlled by neuron signals of the wearer himself, enables the device to move the limb in all planes. The principle of work is as follows. An individual's wish to displace an arm (shoulder, hand) anywhere the system detects thanks to the noninvasive superficial electromyography, i.e. an array of sensors reading biocurrents controlling the muscles. The natural invisible to the eye delay between the appearance of the first myoelectric signals and an actual start of the movement of this or that muscle computer uses to calculate the probable arm displacement, using its digital model of the human limb (additionally, a feedback from the sensors of actual position and the speed of the machine parts are used). As a result the drives of the robot-suit are activated synchronously with muscle contractions and 'press' to the direction the wearer wishes to flex his arm. However, the control system (bioport) is far from being perfect [23–25]. A suit sensitive to myocurrents is capable to enhance muscle strength in people, suffering from neurodegenerative diseases, but this system, to the authors' opinion, requires further improvement [33]. Designs, similar to the described above, were used in the works of other authors who tried to eliminate some of the revealed drawbacks of the prototype [34–36].

Currently, active elaborations are being carried on aimed at filling the gap in fundamental knowledge on exoskeletons. They may be grouped according to the following main aspects:

investigations of kinematic and biomechanic properties of new apparatuses and creation on this basis optimal principles and scheme of their application [17, 37–45];

development of methods of determining systems parameters of exoskeletons and their operation control, allowing the researcher quickly and systemically evaluate different variants of the executive mechanism constructions in accordance with the criteria chosen [46–48];

application of computed analysis of virtual topographo-anatomic media while designing biomechanical systems [49–57];

creation and improvement of the materials and the main units of exoskeletons, ensuring their effective performance [58–66].

The most demanded, judging by the authors' description, references to a number of works of this group of researchers and long-lasting publications on this topic, is the model developed by a team guided by Tariq Rahman from the University of Delaware [33]. The device is called *WREX* (Wilmington Robotic Exoskeleton). It is oriented to children with upper limb impairment, and presents a mobile system of supporting joints, which is attached to the child's active joints and muscles and is fixed to a special jacket or a wheelchair. The limbs move with a slight force and a limited amplitude in 3 dimensions.

However this exoskeleton model is available only in the USA, and requires constant adaptation to the anatomic parameters of the child. Detailed engineering information is not presented in the published materials, making its implementation practically impossible without additional investigations [67, 68].

Currently, descriptions of single investigations on exoskeletons for upper limbs can be found in Russia. Some works are at the stage of designing. A mathematic model of the human arm exoskeleton has been described with the solution of the task of direct and inverse kinematics; inaccuracy of positioning the device in the space, depending on the linear and angular errors, has been also determined [69–71].

The authors of this report have formulated clinical and anatomic criteria, which must be met by exoskeletons designed for the people with the lost functions of the upper limbs. Such requirements were not found in the available literature. The development of criteria was based on the structure and functions of a healthy arm. For this purpose, the material on the active and passive amplitude of the upper limb movements in a healthy man in case of their lost in different conditions, has been analyzed. It was established, that patients with the marked limitations of active mobility in the arms require exoskeletons, with the range of movements approaching the parameters of a healthy human:

1) the elements of the system should replicate the structure of the upper limb;

2) the device should be lightweight and strong;

3) it should be made of safety materials;

4) there must be a possibility of changing the elements as the child grows;

5) price should be affordable for mass consumers;

6) the model should be power source independent;

7) exoskeletons should perform a definite range of movements for the large joints necessary for everyday life activity.

Meeting these requirements will make it possible to create an exoskeleton model for habilitation and rehabilitation of invalids, as well as for their social adaptation [72–74]. The authors also carried out the work on the anatomic compliance of the passive upper limb exoskeleton with the original design.

Presently, exoskeletons are mainly used for rehabilitation and, to a less degree, for habilitation [75], however, a social significance of the latter direction demands widening of its capabilities for adaptation of invalids to usual life by compensating the functions, without which they cannot live independently [72–74].

A number of investigations devoted to the application of the exoskeletons of the upper limbs, can give an idea of a wide scope of their possible usage. In the majority of such reports treatment of post-stroke paralyses of the upper limb is considered [76–86]. Much less researches concern rehabilitation after cerebrospinal traumas [87] and in multiple sclerosis [88], in pediatric practice — for rehabilitation of the upper arm in paralyses, associated with impairment of the brachial plexus in labor [89], and in compensation of grasping function of the hand when a thumb is paralyzed [90]. However, due to the novelty of this direction no clear indications to the application of exoskeletons of the upper limbs are worked out.

Those cases, where the core of the clinical picture is a syndrome of bilateral/unilateral upper flaccid/mixed paralysis (paresis) were of great interest for our developments. A list of these diseases was made [91–97]:

arthrogripposis — a systemic disease of the muscularskeletal system, characterized by contractures and limb deformity, underdevelopment of joints and muscles, and also by fibrosis;

mixed forms of infantile cerebral paralysis;

neuralgic amyotrophy;

spinal amyotrophy — a group of genetic diseases, characterized by the damage of the motor neurons at the level of superior horns of the spinal cord;

brachial plexopathy after Henoch-Schönlein thrombocytopenic purpur, birth trauma ("midwife paralysis", when the clavicle is broken), extra cervical ribs ("cervical rib" syndrome), Pancoast tumor (superior sulcus tumor), malposition of the upper limb during a prolonged operation period under anesthesia, granulamatous vasculopathy associated with herpes zoster virus, exogenous intoxication by dopamine;

Guillain–Barré–Strohl syndrome — acute autoimmune inflammatory demyelinizing polyradiculoneuropathy;

Larsen syndrome — a congenital disease, characteristic findings of which include multiple dislocations of the large joints, distinctive face features and skeletal malformations;

Ehlers–Danlos syndrome (collagenoses);

dystrophic dysplasia;

different forms of congenital myopathy — "central core" syndrome, nemaline myopathy, and other variants of "flaccid child" syndrome;

atonic-astatic form of infantile cerebral paralysis, mixed forms of infantile cerebral paralysis with predominance of limb muscle hypotone.

The syndrome of upper flaccid paralysis occurs in many diseases and may be the cause of invalidization. As upper limbs play the predominant role in the world learning, in patients with upper flaccid paralysis functions of social adaptation are lost, self-care becomes impossible, making the disabled completely dependent on other people [98].

Although the etiology of flaccid/mixed paralysis is various, the clinical picture in such patients seems to be typical. The main signs of this symptomatic complex, demanding exoskeleton application, are the reduction of upper limb muscle strength; restriction of the speed, volume (amplitude) of movements in the proximal and distal parts of the upper limbs with the prevalent aggravation in the proximal parts; muscle hypotonia in the proximal and distal parts of the upper limbs or mixed tonus with hypofunction predominance; low or no arm reflexes (biceps, triceps and carporadial reflexes).

According to the data of the State Statistics Committee, the quantity of people first certified as invalids amounted to 1, 141, 969 or 77.6 per 10,000 of population in 2013 in Russia. Diseases leading to invalidization of population are noted at any age, but they are especially tangible among children and adolescents [99–104].

In this situation of great importance is the necessity of developing such kind of rehabilitation treatment for patients with the syndrome of upper flaccid paresis when there will be something complementary to the drug therapy, and influencing a biofeedback between the central and peripheral parts of the nervous system, and consequently, the direct connection as well.

The solution of this task becomes feasible owing to the innovative direction in bioengineering — designing and implementing upper limb exoskeletons [105–108].

Summarizing the aforesaid, the following conclusions may be made:

1. Models with active principle of work make it possible to perform a larger volume of movements, however, dependence on external power supply units, high cost, design solidity limit their wide application, including medicine. Passive exoskeletons lack these drawbacks. They are power- source-independent, therefore their weight is lower, and the reliability much higher. Price of the passive devices and their maintenance is far lower compared to their active variants.

2. The majority of the known designs are undisclosed and classified military projects. Besides, these models are often intended for healthy people (militaries).

3. An urgent task nowadays is the development of exoskeletons with wider capabilities for adaptation of invalids to everyday life by compensation for the lost functions.

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