Modernization of an industrial passive exoskeleton prototype for lower extremities using rapid prototyping technologies

A O Karfidova*, M V Vasilyev and I G Morozova
NUST ‘MISIS’, Moscow, Russian Federation

*N.Karfid@yandex.ru

Abstract. The work is devoted to an urgent problem: increasing the efficiency of exoskeleton design. Such devices are needed to perform work that requires high physical activity in various production processes [1-18]. Currently, there are no industrial exoskeleton designs that meet the needs of customers [19-30]. To determine the effective design option, analogues of foreign and domestic markets are studied [31-33]. Based on a comparative analysis of characteristics, it is revealed that the Russian exoskeleton developed by Karfidov Lab LTD. [34] has the highest performance in comparison with competitors. However, this design lacks a convenient system for fixing the saddle to support the user, and the exoskeleton has a large weight - 6 kg. As a result of the work performed, some modernization is proposed, taking into account the solution of problems. For this, a solid 3D-model in the SolidWorks environment and design documentation for exoskeleton production are developed. To reduce the exoskeleton weight, it is decided to use plastic parts. Support for the user’s body is provided, made in the form of a vest, as well as fixation system in the form of belts located on the foot, lower leg and thigh. It is decided to install a gas spring from the manufacturer Suspa, model Varilock EL2-111-79-600N, which enables to increase the shock absorption when the exoskeleton is active. To increase the strength of plastic parts, a reinforcement method is used. A saddle is introduced that provides a soft contact between the user and the system in the active and passive positions of the exoskeleton.

1. Introduction

The main purpose of an industrial exoskeleton is to provide the worker with additional power to reduce the risk of injury while performing production tasks. In addition, the device must be comfortable enough to use.

Studies of exoskeleton prototypes have shown that initially they are not always able to meet the requirements of users [31-33]. In some cases, the use of the device leads to an increase in the load on other parts of the body that are not involved in the performance of the main technological operation. For example, it has been proven that exoskeletons BNDR, HappyBack, and Bendezy reduce the muscle activity of the spine by 21–31%, but increase the muscle activity of the lower extremities, which is generally not a positive result [32].

A key factor in exoskeleton rejection is local discomfort caused by the force applied to the body at the exoskeleton interface (contact pressure). If the device is improperly designed, the user can experience significant discomfort and even injury.
In addition, during the development of an exoskeleton, one may encounter the following problems: low movement speed, individual need for anatomical positioning, movement with a limited amplitude. In connection with the above factors, the technologies aimed at ergonomics and ease of use were used in the development of the exoskeleton.

It was decided to develop a passive exoskeleton for the lower extremities. In contrast to the active one, the redistribution of kinetic energy and residual human strength is used as a source of energy in such a structure, the use of additional motors and storage batteries, which are often massive and heavy, is excluded. The passive device does not depend on an external power source, so its operating time is unlimited and bulkiness can be minimized.

A passive exoskeleton uses energy from the lower extremities, which is subsequently processed to help the user perform a certain movement. A number of different strategies is used to reduce energy costs to users. Some designs focus on nearly invisible weight support systems, while others use complex spring systems in an attempt to save energy by reducing muscle stress.

2. Problem formulation

In a passive exoskeleton, ankle kinematics is associated with the cyclic potential arising from walking, which reduces metabolic costs without relying on an external power source. This is due to the fact that some tendons, such as the Achilles, serve to store energy [37]. During the support phase of walking, the foot remains flat on the ground, while the center of the body mass moves over the supporting limb. This is supported by the study [38], which presents a passive exoskeleton using a standard compression spring running parallel to the Achilles tendon. Since the tendon is stretched during the stance phase of a normal gait, some of the energy is stored in the compression spring. Therefore, during the stance phase of walking, the exoskeleton of the ankle joint reduces metabolic costs when a person walks using passive elements [37–39]. Thus, while powered devices successfully reduce an individual’s energy consumption while walking, passive devices, on the other hand, try to match their performance.

To determine the optimum design of the exoskeleton, a study of the foreign segment of exoskeletons was carried out. The main aspects of the study were actuators, design and attachment components of the exoskeleton interface. More than 50 names of exoskeletons were investigated. It was found that the most popular were the development of exoskeletons based on elastic drives and a rigid structure (85% of the examined exoskeletons) [39]. The most common type of actuation is the use of serial elastic actuators (60% of the examined exoskeletons). Most actuators used linear springs (44% of the exoskeletons studied) due to their commercial availability, ease of implementation, and low cost. Most elastic-actuated exoskeletons had only one brace per leg segment (i.e. thigh or lower leg). The proposed solutions are very diverse, making it difficult to determine the best design option. However, there are no generally accepted criteria, sufficient technical information and performance indicators for the design of a lower limbs’ exoskeleton. Most actuators are the result of a trial and error design process based on practical experience already acquired.

Despite the absence of specific criteria and indicators of the quality of developments, modern sources provide a large amount of information about foreign experience in the development of exoskeletons of the most diverse types. The segment of the market for imported exoskeletons is represented by at least sixty different names introduced into use [39]. At the same time, there are no analytical and experimental data on the performance indicators of existing devices, specific methods and technologies for their manufacture.

The market for Russian developments of industrial exoskeletons for lower extremities is negligible and obviously requires further development. The market for existing Russian industrial exoskeletons is represented by only a few names. Their comparative analysis is presented in Table 1.
Table 1. Comparative characteristics of domestic industrial exoskeletons [35-36]

| Criterion                                      | ‘Nornickel’ exoskeleton | X-Soft | ‘Karfidov Lab’ LTD. exoskeleton |
|-----------------------------------------------|-------------------------|--------|---------------------------------|
| Weight, kg                                    | -                       | 8      | 6                               |
| Cost, rub                                     | -                       | 70 000 | 150 000                         |
| Operator’s height, cm                         | 160-195                 | -      | 165-195                         |
| Maximum operator weight, kg                   | -                       | -      | 100                             |
| Maximum weight of loads to relieve the load from the lumbar region, kg | 60          | -      | -                              |
| Element material                              | -                       | Steel  | Steel                           |

The paper analyzes a promising design of the lower extremity exoskeleton, created on basis of ‘Karfidov Lab’ LTD., as the most optimal in comparison with its competitors, with the aim of improving it through modernization. The development and the block diagram of the main elements of the exoskeleton are shown in Figure 1. Modernization should reduce the impact of the identified deficiencies on the exoskeleton performance.

3. Purpose of work
Modernization of the industrial exoskeleton of lower extremities, created on basis of ‘Karfidov Lab’ LTD., in order to increase its operational properties.

4. Methods and materials
To study the designs of industrial exoskeletons, a review of foreign electronic information resources was carried out. As a result, about 60 publications were identified, structured according to three criteria: actuators, design and attachment components of the exoskeleton interface. A review of Russian sources was also carried out, resulting in 3 optimum designs, which were identified and compared. For modernization, the design of an industrial exoskeleton developed by ‘Karfidov Lab’ LTD. was chosen. To determine the design flaws, information from the developers on the exoskeleton design and the technical solutions incorporated in the model was obtained and analyzed. On their
basis, design flaws that need to be improved were identified: low ergonomics, discomfort in the back of the user’s thigh during operation of this design, lack of fixation of the exoskeleton in a sitting position, excessive weight (the exoskeleton weighs is 6 kg) and poor positioning of the lever mechanism.

Modernization is associated with the use of solutions aimed at minimizing the listed problems.

When designing, first of all, the kinematics of the exoskeleton was considered. In the original design, a Pneumax pneumatic actuator with a working pressure of 10 bar and a stroke of 80 mm was chosen as the power element, but it had several disadvantages, and as a result the use of a controlled gas spring was proposed in the modernized design. Such a spring will enhance the comfort and ergonomics of the wearer, allowing for a comfortable sitting position. Such a lockable gas spring will allow it to be fixed in any travel position, be it an elastically lockable lock or a rigid one. The following types of springs are considered as drive options: Suspa Varilock EL2-111-79-600N and Suspa Varilock HY1. The selection of the following springs is based on consultation with the manufacturer. Their comparative characteristics are shown in Table 2.

| Parameter name                        | Suspa Varilock EL2-111-79-600N | Suspa Varilock HY1 |
|--------------------------------------|---------------------------------|-------------------|
| Maximum load in the direction of compression, N | 6500                           | 6500              |
| Maximum load in the direction of expansion, N  | 3500                           | 3500              |
| Tube diameter, mm                    | 22                              | 22                |
| Tensile forces, N                    | 200-800                         | 200-800           |
| Block system                         | Elastically lockable            | Rigid in the direction of extension |
| Shock absorbing effect               | Obligatory                      | Undesirable       |

According to the results of comparative characteristics, an elastically lockable gas spring by Suspa, Varilock EL2-111-79-600N, was selected as a pneumatic actuator. It is intended for use in chair backs. Such a gas spring is elastically locked in cases where a residual springing is required by the user. It is recommended if the blocking function is required to have a cushioning effect. In this case, impulse peak loads can be attenuated or completely overcome.

The gas spring actuation mechanism is as follows - on the user’s display there is a button for accepting a sitting position. When pressed, unlocking occurs, as a result of which the stem can be freely moved while the button is held. During this time, the user either crouches or rises. The gas spring is shown in Figure 2.

![Figure 2. Gas spring in design](image)
A knee joint has been developed, which is responsible for turning the axis of joint rotation to realize the possibility of folding the structure when the user is deeply seated in a position that is suitable for him. In the kinematics of the original version, two isolated mechanisms were used, one for each leg in the form of three-link mechanisms with two joints: a rotational one in the knee joint and a spherical one in the ankle joint. In the past, protruding links were present, which reduced the convenience of the user and, in conjunction with the pneumatic drive, provided a rigid landing in the ‘sitting’ mode. The initial kinematics and the proposed solution are shown in Figure 3.

In the course of design development, the options of materials used were analyzed. To reduce the mass of the structure, it is necessary to use materials and methods of manufacturing the prototype and its components, taking into account the small-scale assembly of the product. According to the experience of the existing development by ‘Karfidov Lab’ LTD., the use of steel made the structure heavier. One of the options was the use of aluminum alloys, but calculations showed that with this option the proper weight characteristic will not be achieved. Therefore, it was decided to use engineering plastic or carbon fiber as a material that could later be used in the exoskeleton production by small-scale molding technology in silicone molds. Nevertheless, bushings, axles, hinge elements, adjustment elements were proposed to be made of aluminum or steel alloys, depending on the required strength. For strapping elements, it was possible to use laser cutting technologies [16].

As for adjusting the user’s height from 165 cm to 195 cm and fixing the exoskeleton’s height, since the existing version used a cylindrical clamp with a hardened core, which proved effective, it was decided to leave it as it is. The lower support clamp is shown in Figure 4.
As for the top support clamp, the second clamp, shown in Figure 5, is located under the seat. This clamp provides a change in the seat position, the introduction of which in the modernized design is considered an innovation.

![Cylindrical clamp with hardened core on the upper support](image)

**Figure 5.** Cylindrical clamp with hardened core on the upper support

The seat shown in Figure 6 was designed with holes with vacuum inserts to provide a soft fit to the human thigh while also reducing slipping and increasing comfort. The rounding diameter was chosen to be optimal for different thigh thicknesses. The seat itself is supposed to be made of plastic parts, as for the fastening elements, for reliability they must be made of aluminum alloys.

![Seat model](image)

**Figure 6.** Seat model

To reduce weight of the design, predominantly plastic elements were chosen. Parts made from plastics must have a shape that meets the requirements of the part pressing process, and the walls must be almost of the same thickness. In this regard, during designing, great attention was paid to the accuracy of the development of future plastic elements. To reduce surface wear and increase the mechanical strength of the product, as well as its wear resistance and other performances, it was
advisable to use reinforcement of plastic parts with metal plates. Such metal plates for the bottom support are shown in Figure 7.

![Figure 7. Reinforcement of plastic parts with metal plates for bottom support](image)

The same principle was used for the top support. The model of the upper support reinforcement is shown in Figure 8.

![Figure 8. Reinforcement of plastic parts with metal plates for upper support](image)

The metal plates had holes. This was due to the lightweight construction, since the main requirement was low weight. Options of holes for metal springs were also considered at the technical design stage (Figure 9), but it was decided to use an ornament with triangular cutouts, as the lightest and most durable.

![Figure 9. Hole options for reducing weight of metal plates](image)
As for modernization associated with the introduction of the exoskeleton fixation system as a single structure, which includes an adjustable shoulder harness, an adjustable belt, a corset with a rigid insert and shoulder straps to relieve the lumbar and thoracic spine and the straps for attaching to the user’s shoes and legs, for the lower support to ensure fixation of the user’s foot, the solution presented in Figure 10 was chosen. This solution provides for a hole to accommodate fabric belts that connect the structure to them. The solution is designed in such a way as to attach to the user’s feet and shoes from above and behind, securely fixing the position and not interfering with the free movement of the exoskeleton in the passive position.

![Figure 10. Fixing the foot position](image)

### 5. Obtained results and their analysis

As a result of technical design and substantiation of the choice of components, the design of a passive exoskeleton for lower extremities was developed, the assembly of which is shown in Figure 11.

![Figure 11. Assembled exoskeleton design](image)

This design, in contrast to the original development of ‘Karfidov Lab’ LTD., has a number of advantages, such as presence of a seat and fasteners for fixing the user, a folding mechanism instead of a lever mechanism, a lightweight construction of 4 kg, mainly consisting of plastic parts and reinforced with metal plates with recesses. Thus, the result of work in the course of technical design enables you to move on to the next stage - manufacturing. Directly before manufacturing, technical
documentation for the projected model was developed. Since most parts are designed for use in the manufacture of plastic parts, it is therefore proposed to produce plastic parts by small-scale prototyping using the casting method in silicone. Bushings, axles, hinge elements, adjustment elements are proposed to be made of aluminum or steel alloys, depending on the required strength.

6. Conclusion
As a result, ways of modernizing the ‘Karfidov Lab’ industrial exoskeleton of lower extremities were proposed. Achieving this goal will improve the following operational properties of the investigated structure:
- weight reduction by 2 kg (from 6 kg to 4 kg) due to the use of plastic parts and their reinforcement;
- increased user comfort due to unloading of the lumbar and thoracic spine by using a harness;
- reduction of static tension in the muscles of the neck-shoulder region and back to prevent the development of fatigue and maintain a rational working posture due to the introduction of a working seat;
- adjustment of the upper support along the length due to introduction of a cylindrical clamp for individual physical characteristics of a person;
- reduction of the production cost due to the use of plastic parts instead of steel ones, manufactured by rapid prototyping (casting in silicone molds);
- reduction of impulse peak loads due to the use of an elastically blocked gas spring.

In the course of technical design, to solve the identified problems of the initial design of ‘Karfidov Lab’ LTD., options for structural units and components that meet the requirements were proposed. For ease of use, predominantly plastic molded parts were used. The fixing system in a modernized design was designed in the form of straps located on the foot, lower leg and thigh, as well as support for the body in the form of a vest. Instead of a pneumatic spring, a gas spring was used to increase shock absorption when the exoskeleton is active. The reinforcement method was used to increase the strength of plastic parts. A seat was introduced that provided a soft contact between the user and the system in active and passive positions.

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