Experimental studies of a soft industrial exoskeleton in work-related activity for the evaluation of its operational efficiency

Andrey Yatsun*, *Maria* Shcherbakova, and *Andrey* Malchikov

Southwest State University, Kursk, Russia

Abstract. For conducting the experiment under laboratory conditions, a dedicated workplace was designed to simulate the activity of lifting / lowering a 20 kg load to a height of 0.7 m in the “Squat” and “Stoop” styles. To implement this study, the following methods were employed: “motion capture” to assess the mechanics of movements in the lumbar spine; a non-invasive method for measurement of the key biological indicators as a comprehensive assessment of the state of the cardiorespiratory system; electromyography (EMG) as the main method for assessing the bioelectrical activity of muscles; interviewing volunteers (on a 10-point scale) as a method of subjective assessment of their physical condition and performance. A study conducted as part of the work meant to determine the effectiveness and safety of using a soft industrial exoskeleton during work-related activity, including the elimination of the harm from stereotypic work movements, showed a decrease in the activity of the measured muscles when using a soft industrial exoskeleton, which also indicates a decrease in human fatigue that increases the effectiveness of its operation.

1 Introduction

Currently, despite the ongoing trend towards a decrease in the volume of manual labor, in various sectors of economics it is still impossible to abstain from hard physical labor and it remains the main risk factor for injuries and the development of occupational diseases, including the musculoskeletal system [1].

The Lancet Rheumatology predicts that by 2050, approximately 843 million people will suffer from low back pain, based on projected population changes. A report by Manuela Ferreira (University of Sydney) on the global burden of low back pain with all that it entails and its modification from 1990 to 2020 found that this figure has increased by an average of 60.4 percent over 30 years [2].

Occupational morbidity, directly related to the consequences of physical overload and overstrain of individual organs and systems, ranks second in the structure of occupational pathology, depending on the harmful production factor affecting it and amounts to about 25%. The lumbar spine often suffers, pain can be caused by various reasons, but in 90% of cases the pain is caused by problems with the spine and back muscles, which, in turn, arise

---

* Corresponding author: ayatsun@yandex.ru

as a result of physical work activity and, in particular, from stereotypic movements, which cannot be avoided in any activity related to loads handling [3].

Stereotypic work movements are typical / repetitive movements performed by workers in the course of work-related activities (for example, lifting and moving heavy objects). These movements can place undue stress on the body and, over time, lead to injuries including carpal tunnel syndrome, back pain, and torn ligaments and tendons, ultimately leading to partial or complete disability. Currently, more than 100 different injuries are known that are identified as consequences of stereotypic movements [4].

In this regard, a relevant and promising direction is the development of technologies for creating soft industrial exoskeletons that can protect not only the upper part of the human musculoskeletal system from excessive physical exertion, but also significantly reduce the risk of complications from stereotypic movements [5].

A significant role in forming conclusions about the safety and physiological effectiveness of the soft industrial exoskeleton [6] is played by their medical and biological assessment. With the help of modern approaches to the study of the functional state of a person, used in occupational medicine, sports medicine, functional diagnostics, rehabilitation and other areas, it was possible to determine the following methods for the given research:

"motion capture" to assess the mechanics of joint movements;

– measurement of basic biological indicators as a non-invasive method of cumulative assessment of the human cardiorespiratory system condition [7];

— electromyography (EMG) as the main method for assessing the bioelectrical activity of muscles [8–13];

In relation to the current problem, the purpose of the study is to evaluate the safety and effectiveness of the use of a soft industrial exoskeleton in simulated work-related conditions, including stereotypic work movements.

2 Methods

The development of a work-related activity model was carried out in the laboratory of the Federal State Budgetary Educational Institution of Higher Education "MiR" of the Southwest State University based on the indicators of the workload and the characteristics of work (body) postures and stereotypic movements of specialists in professions where a worker lifts and (or) lowers a load manually [14,15].

To simulate labor activity, conditions were created similar to those in which a specialist works, performing work with a load, applying only his own muscle strength. A model of a workplace in the laboratory environment is presented in figure 1.

The test sample featured a Lowebacker soft exoskeleton (Fig. 2), designed to reduce the negative impact of dynamic loads on the upper body associated with lifting heavy objects and bending the body. The soft industrial exoskeleton comprises an upper body vest connects to the lower body via length adjustable elastomers with adjustable straps and cuffs. With the help of elastomers that absorb some of the stress during contraction and the vest that distributes it evenly, less stress is placed on the lumbar spine when lifting. When lowering the load, a small force is required to stretch the elastomer, which provides support and requires less effort from the user to smoothly hold and lower the load [16,17].

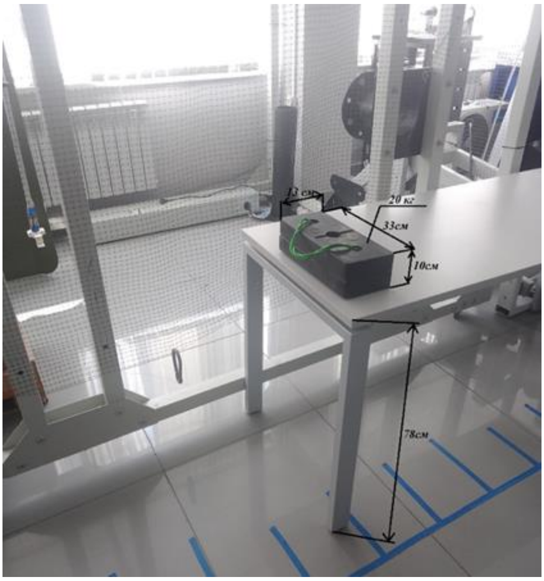

Fig. 1 Laboratory workstation model with a load.

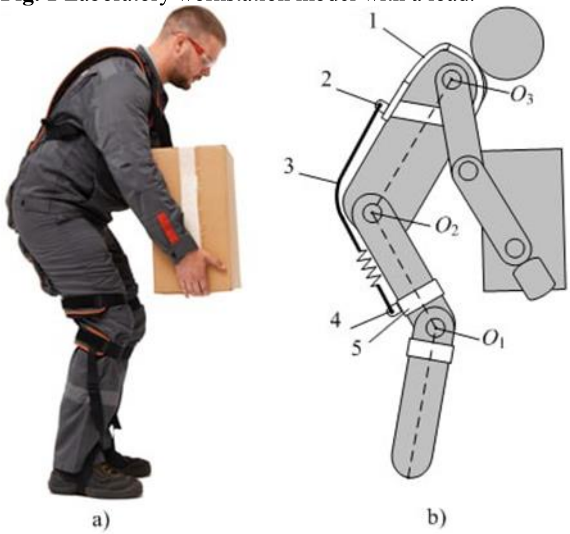

Fig. 2 Diagram of the tested exoskeleton: a) general view of the soft industrial exoskeleton; b) diagram of a person in a soft industrial exoskeleton, where: 1-5 units of the soft industrial exoskeleton (3-elastomers); O1-O3 – joints in which bending occurs when working

Four healthy men (age 22 ± 2 years, height 179.0 ± 4 cm, body weight 79.0 ± 10.5 kg, body mass index 24.7 ± 2.8) were recruited as volunteers subsequent to the results of occupational health assessment and diagnosed "healthy". Each of the volunteers simulated work activity both without and with the use of the soft industrial exoskeleton.

The effectiveness of using the soft industrial exoskeleton was assessed according to [1]:

– indicators of the general condition of the volunteers;

– level of fatigue and psychophysiological state of the volunteers for the entire period of simulated work activity (according to the subjective assessment of volunteers);

– indicators of the cardiorespiratory system of the volunteers;

– fatigue of the measured muscles involved in performing work movements;

– indicators of static coordination of the volunteers;

– indicators of labor productivity (for testing aimed to determine the duration of comfortable work with and without the application of the soft industrial exoskeleton).

The assessment of the general condition of the volunteers was carried out through external examination, measurement of the main indicators of the functional state and a questionnaire (assessment on a 10-point scale), which included a subjective assessment of own sensations when performing the movement in the lumbar spine, a subjective assessment of physical condition and performance, as well as the occurrence of discomfort or pain. Interviewing for the cases of soft industrial exoskeleton application included special questions assessing the following parameters:

– assessment of well-being in comparison with well-being before the experiment;

– assessment of the comfort of working with soft industrial exoskeleton compared to working without using the soft industrial exoskeleton ;

– assessment of the usability of the soft industrial exoskeleton while work is performed;

– assessment of the ease of use of the soft industrial exoskeleton when resting or performing operations not related to work;

— assessment of the convenience and speed of putting on and removing the soft industrial exoskeleton;

– assessment of the speed of adaptation to the use of the soft industrial exoskeleton.

Muscle activity and fatigue were assessed by EMG using the Callibri Muscle Tracker electromyography system. The main characteristics of the applied EMG sensor are presented in Table 1 [18].

Table 1. Characteristics of the EMG sensors.

Parameter	Value
Analysis of recurrent movements in time	yes
Description of movements by the set of parameters	Acp, Amax, Tcp, υ, S
Analysis of the repetition rhythm and variations in the motion power during activity	yes
Calculation of integral EMG	yes
Channel configuration with selectable overlay location	yes
Protocol-Test, which is interpreted as a Muscle group	yes
Exercise (Activity)	yes
Automatic system for identifying areas of EMG activity	yes
Number of simultaneously used sensors	up to 4
Type of potential registration	bipolar
Wireless communication interface	yes
Recorded signals	EMG
Range of measured EMG voltages	0-2.4 V
Range of the wireless communication channel	up to 2-5 m
Operating frequency	2,4 GHz
Installation	Stick-on electrodes

To assess the physiological state of a person, as well as the impact of the exoskeleton on him under the conditions of simulated work activity, a multi-parameter patient monitor (KN-601M) was used. The parameters assessed by the displayed data are NIBP (pressure), heart rate (pulse), respiratory rate, SpO2 (saturation) and temperature [19].

When studying the physiological effectiveness of the soft industrial exoskeleton, the condition of the back muscles in the lumbar spine (the latissimus dorsi) was assessed (Fig. 3) for four states in volunteers: performing work on lifting and lowering a 20 kg load in the

“Stoop / Bend” position and in the “Squat” style without the soft industrial exoskeleton on and doing the same work with the soft industrial exoskeleton on.

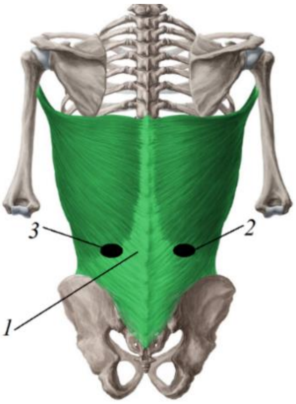

Fig. 3 Layout of sensors for recording muscle activity: 1 – area for installing sensors; 2.3 – right and left sensors, respectively.

The location of the sensors is determined by the fact that when performing any work on moving a load, the lumbar spine, in particular the latissimus muscles, is always involved and takes on a large load. Stereotypic flexion / extension of the back in the lumbar spine, often unavoidable, cause significant harm to a person’s health and performance. It is also important to take into account that the work of the latissimus muscles also involves secondary muscles - the muscles of arms, shoulders and thoracic region [20,21], which work together and when the latissimus muscles work, part of the load will be transferred to the secondary ones, which, as a result, can be overloaded , that will lead to a “domino effect”.

It is also worth considering that even paired human muscles, such as the latissimus, have slight asymmetry; for example, a right-handed person has more developed muscles in the right hand. Symmetrical muscles also have varying degrees of activity due to many factors, both internal and external, that influence a person throughout life [22]. Based on this, the results obtained for each side should be averaged, assuming that the muscle activity is absolutely the same, since our task is to determine the activity of a pair of muscles, and not to identify the asymmetry between them, which is the norm with minor deviations in the result of an activity.

Despite the fact that work with lifting / lowering a load, according to the recommendations of doctors and occupational hygiene specialists, should be carried out in the “Squat” style, nevertheless, the experiment was carried out in the “Stoop” style. It is accounted for by situations, in which the “Squat” style is not applicable, but the work with a load still needs to be performed, for example, it is necessary to remove a load from a deep box, or place it there.

The study of the effectiveness of the soft industrial exoskeleton application was carried out in two stages. At the first stage, simulation of work activity was carried out without the use of the soft industrial exoskeleton, at the second stage - with the soft industrial exoskeleton used. Testing was carried out before the start of the simulation of work activity - background testing, during breaks - intermediate testing and after the simulation - benchmark testing at both stages of the research. The research diagram of the work activity simulation is presented in Figure 4.

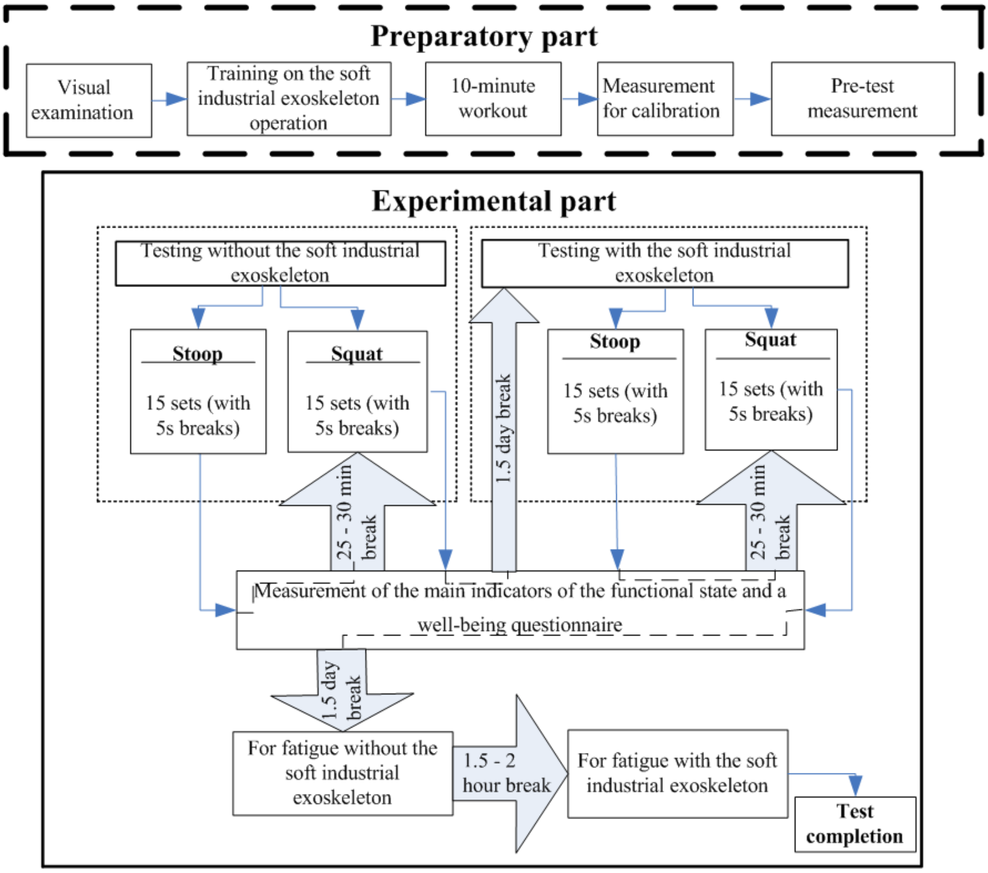

Fig. 4 Work-related activity simulation scheme.

3 Conducting the experiment

Prior to the test, the volunteers completed a 10-minute warm-up consisting of dynamic stretching of the upper and lower body. After installing the functional activity sensors, the participants were asked to perform two tests for the muscles under study for the purpose of subsequent calibration of the sensors.

According to the developed plan of the experiment, the participants were required to perform 15 sets, including lifting a 20 kg load (0.33 × 0.13 × 0.1 m3) from the floor to a table, and then lowering the load from the table to the floor, in one of the two lifting styles (Fig. 5) [23,24]:

1) stoop – bending (flexion) at the waist and weak bending at the knees, extension of the lower back and knees;

2) squat - hip flexion, knee flexion, straight back, hip extension, knee extension, straight back.

Each approach includes 2 phases: 1st phase – lifting the load onto a given surface (table), 2nd phase – lowering the load to its initial position (on the floor), and, in turn, each phase is divided into 6 steps (Fig. 5), also each phase includes 3 stereotypic movements:

1) stooping / squatting to pick the load;
2) load grip;
3) lifting / lowering the load.

In two of them, the consequences arising from stereotypic movements are significantly reduced, since stooping / squatting and lifting / lowering are directly related to the lumbar spine, which is to be unloaded by the use of the tested soft industrial exoskeleton.

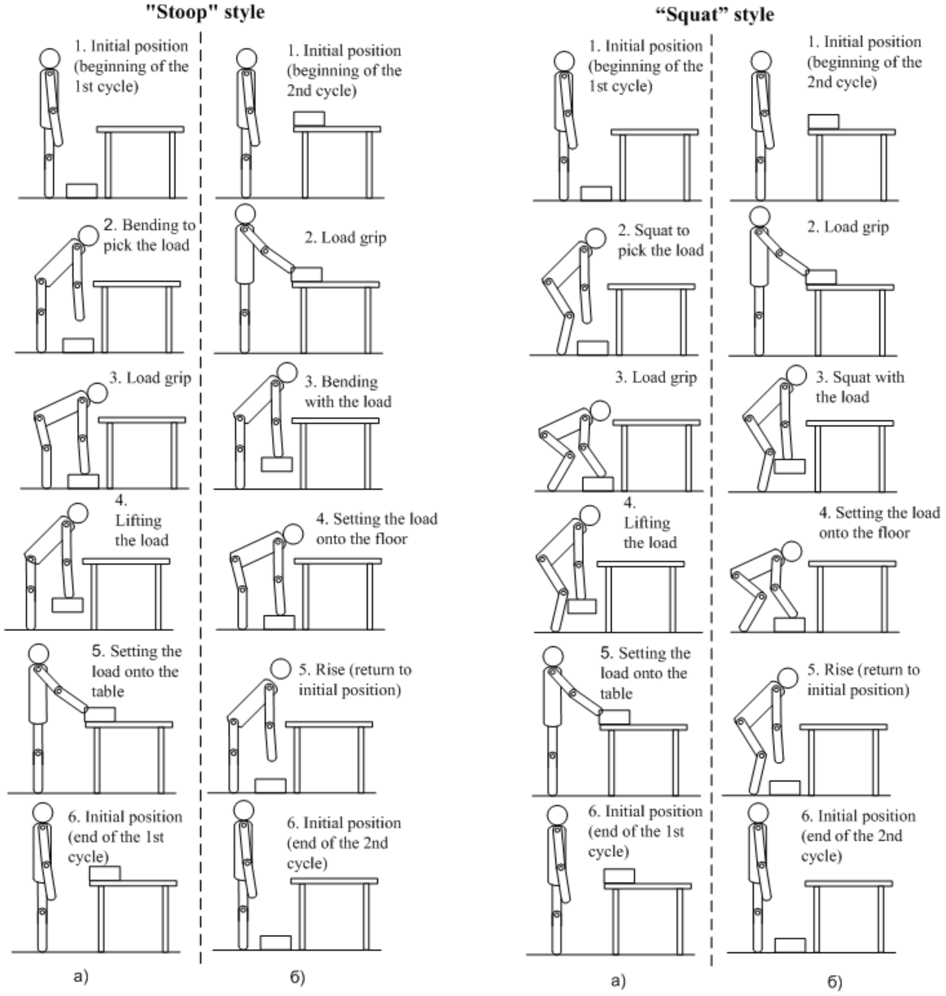

Fig. 5. Performing stereotypic movements of one set in two styles “Stoop” and “Squat”: a) 1st phase of lifting a load; b) 2nd stage of performing a load lowering.

Each trial began with a standard posture—standing upright, arms at sides—to reduce the motion sensor reading to zero. The rise frequency was adjusted to 2.5 seconds up/down. Each set included 2 stoops (bends) /squats and 2 lifts. Each type of lift has been tested using elastomers designed to withstand loads up to 55 kg. Between lifting the load, rest was given for about 5 seconds, between lifting styles - about 25-30 minutes, and between tests without and with the soft industrial exoskeleton - 1.5-2 hours.

According to the plan, the experiment was conducted to assess the duration of comfortable work (on fatigue) without the use of the soft industrial exoskeleton and with the soft industrial exoskeleton on. The experiment was carried out in the “Squat” style, as the most optimal way to perform work with lifting / lowering a load, within which the volunteers performed a comfortable number of sets.

4 Results

Data obtained from the studies using previously described methods showed a significant discrepancy between the recorded values of the indicators of the volunteers working without and with the soft industrial exoskeleton on. Figures 6-7 present in the form of a diagram the results of the performance of latissimus muscles in the simulated activity according to the peak values of the muscle signals.

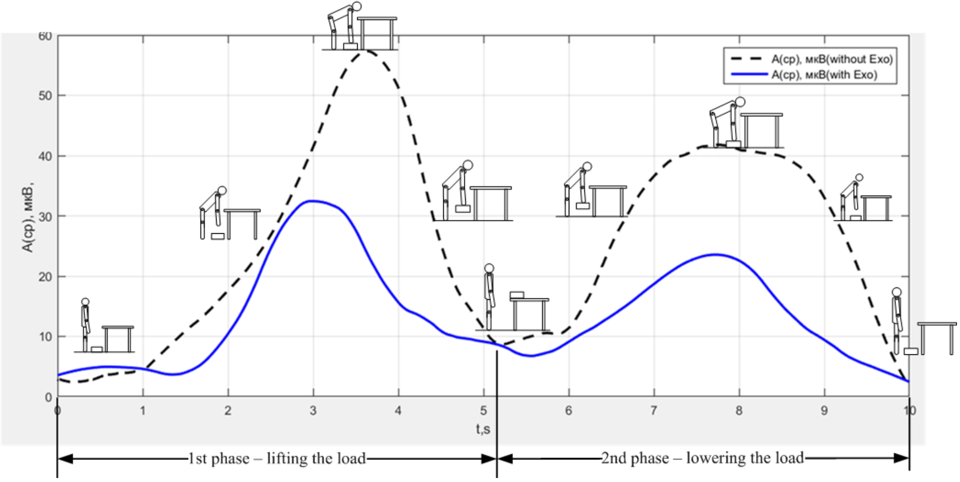

Fig. 6. Graphs of average activity of the latissimus muscles for one set in the "Stoop" style for tests without and with the use of the soft industrial exoskeleton.

Analyzing the data obtained, presented in Figure 6, we have that when performing work in the "Stoop" style, muscle activity when working in the soft industrial exoskeleton decreased significantly. Thus, for the phase of lifting the load, a decrease of 40% is observed on average, as well as for the phase of lowering the load. Based on this, we can conclude that even with an undesirable method of lifting / lowering the load, the load on the lumbar spine when using the soft industrial exoskeleton is significantly reduced, thereby reducing the possible risks of complications caused by the method applied.

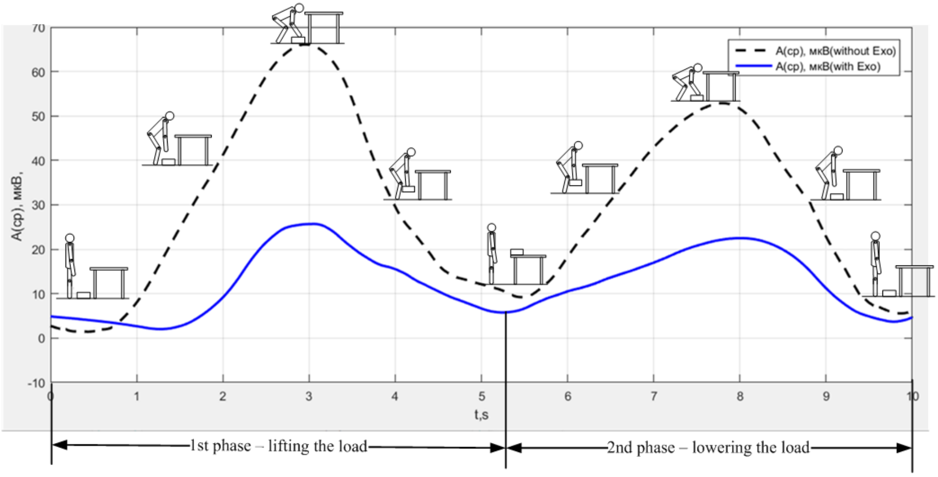

Fig. 7. Graphs of average activity of the latissimus muscles during one set in the "Squat" style for tests without and with the use of the soft industrial exoskeleton.

Analyzing the data obtained, presented in Figure 7, we have that when performing work in the “Squat” style, muscle activity when working in the soft industrial exoskeleton decreased significantly. Thus, for the load lifting phase there is a decrease of an average of 60%, and for the load lowering phase - by 55%. The difference between the phases is explained by the fact that during the process of lifting a load, previously stretched elastomers tend to return to their original position, thereby pushing the person up, making it easier for him to lift.

According to the data obtained (Fig. 6-7), it is obvious that a person needs to make less effort at the stage of lowering the load, regardless of whether he uses an exoskeleton or not. At the same time, if we analyze only the load lowering phase of the two styles, then when using the soft industrial exoskeleton in “Stoop”, the decrease in activity occurs on average by 20%, in “Squat” - by 8%.

In the first second of the simulation (Figure 6-7), we can notice that muscle activity is by an order of 1 percent higher when using the exoskeleton; the person has not yet started doing the work and is in the initial position. This is explained by the fact that the muscles of the shoulder girdle are subject to load in the form of the mass from the exoskeleton. As mentioned earlier, the muscles of the shoulder girdle are interconnected with the latissimus muscles, thereby, transferring part of the load. But when returning to the starting position after the 1st stage of the work performed, muscle activity in the exoskeleton is lower than without it. This is due to the fact that during work the measured muscles, as a rule, were subjected to lesser load, which was partially taken over by the soft industrial exoskeleton.

Analyzing the graph data (Fig. 6-7), we find that the use of the soft industrial exoskeleton is more effective in the “Squat” style, since the percentage of decrease in muscle activity is much higher compared to the “Stoop” style.

The data presented in Figure 8 shows how much muscle activity was reduced in phase 2 compared to phase 1 for each of the 4 volunteer conditions across the trials.

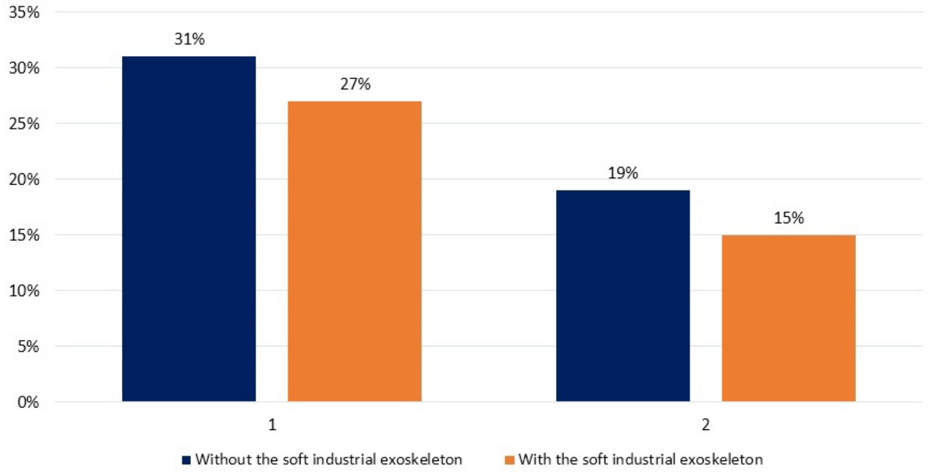

Fig. 8. Percentage of decrease in muscle activity in phase 2, where 1 – “Stoop” style; 2 – “Squat” style.

Regarding the load relative to the phases, the results obtained (Fig. 8) indicate that the use of the soft industrial exoskeleton is more effective in the “Stoop” style. In this case, the “Squat” style is preferable, since when using the exoskeleton, the load on the muscles is less and more evenly distributed between phases. Thus, the difference between phases in “Squat” using the soft industrial exoskeleton is 12% less.

Based on the results of measurements of the key physiological parameters, the following results were obtained confirming the effectiveness of the use of the soft industrial exoskeleton:

- saturation after the experiment using the soft industrial exoskeleton had the same indicators as in the rest state, whereas after the experiment without the soft industrial exoskeleton it decreased by 1%;

- pressure after the experiment without using the soft industrial exoskeleton increased by 8-20/0-6 units compared to the values at rest, whereas when using the soft industrial exoskeleton it increased only by 0-2/0-1 compared to the rest state;

- the heart rate after the experiment without using the soft industrial exoskeleton increased by 11-20 units compared to the values at rest, and when using the soft industrial exoskeleton increased by 10-16 compared to the rest state;

The results of the experiment assessing the duration of comfortable work without the use of the soft industrial exoskeleton and while applying it are equally important, since, when working with a load, a person may not comply with the established time ranges for reducing fatigue, which are prescribed by various standard methods and instructions for labor safety. The results obtained showed that, on average, muscle activity decreases by 50%, which has a positive effect on the duration of comfortable operation in the soft industrial exoskeleton (Fig. 9). The results have also shown that, as estimated, the duration of comfortable work in the soft industrial exoskeleton increases by 18%. According to the volunteers, it is easier to work with the soft industrial exoskeleton on as the feeling of fatigue occurs later.

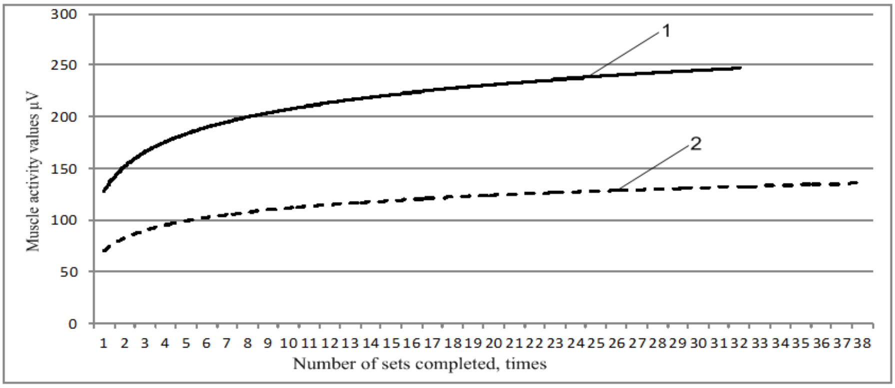

Fig. 9. Graphs of muscle activity while executing the experiment on the duration of comfortable work, where 1 – values of muscle activity when performing work without the soft industrial exoskeleton; 2 – values of muscle activity when performing work in the soft industrial exoskeleton.

A survey of the volunteers on special issues for the cases of using the soft industrial exoskeleton gave the following results:

- the assessment of the convenience and speed of putting on/removing the soft industrial exoskeleton showed that difficulties arose during the first few times of putting on/taking off;

- the assessment of the speed of adaptation to the use of the soft industrial exoskeleton showed that about 2-3 hours are required for adaptation and comfortable operation;

- the assessment of the usability of the soft industrial exoskeleton during rest or performing operations other than work showed that after the adaptation period, the exoskeleton feels like outerwear and does not cause discomfort. Except for the cases when the volunteer had initially misjudged the convenience of applying the soft industrial exoskeleton to him, which subsequently led to discomfort, the elimination of which required additional individual adjustment, after which the complaints were handled.

According to the volunteers' responses, they did notice a difference in favor of using the soft industrial exoskeleton, and everyone noted that the soft industrial exoskeleton made performing “Squat” style load activities significantly easier. The assistance of the soft industrial exoskeleton is especially noticeable after a number of completed sets.

5 Conclusions

Modern approaches to determining the functional state of a person during work-related activities associated with stereotypic movements, including measurement of basic biological indicators, "motion capture" and the use of electromyography, make it possible to give an objective physiological assessment of the effectiveness, and most importantly, the safety of the application of the soft industrial exoskeleton in laboratory conditions.

The results of this research based on the above given methods, which can complement existing approaches to studying the functional state of manual workers, have confirmed the effectiveness and safety of using the tested soft industrial exoskeleton in load-bearing conditions, as well as the minimization of risks, arising as a result of stereotypic movements in the lumbar spine.

It is worth noting that when working with a load, some stereotypic movements that occur at local load (with the participation of the muscles of hands and fingers) and at regional load (when working with the predominant participation of the muscles of arms and shoulder girdle) cannot be neutralized by the use of the tested soft industrial exoskeleton [25].

Based on the results of the present study, we can conclude that the tested soft industrial exoskeleton sample, as far as we have been able to assess, is effective and safe.

However, it is advisable to formulate the conclusion about the complete safety and clearly high efficiency of using this sample of the soft industrial exoskeleton at workplaces in real work conditions separately, but taking into account the results of the present paper, the characteristics of production, including the occurrence of harmful and (or) dangerous factors, features of the technological process, production operations, and equipment used [1].

This research is supported by Russian Science Foundation https://rscf.ru/project/23-29-00823

References

1. A. M. Geregej et al., Analiz riska zdorov'yu **3**, 148-159 (2020)
2. M. Ferreira et al., *The Lancet Rheumatology; Medical gallery of Blausen Medical 2014* (WikiJournal of Medicine, 2023)
3. I. A. Orlov et al., Medicina truda i promyshlennaya ekologiya **59(7)**, 412-416 (2019)
4. R 2.2.2006-05. Gigiena truda. Rukovodstvo po gigienicheskoj ocenke faktorov rabochej sredy i trudovogo processa. Kriterii i klassifikaciya uslovij truda (utv. Glavnym gosudarstvennym sanitarnym vrachom RF 29.07.2005) Prilozhenie 15. Metodika ocenki tyazhesti trudovogo processa (2005)
5. A. E. Karlov, A. A. Postol'nyj, E. V. Savel'eva, *Nauka i obrazovanie: otechestvennyj i zarubezhnyj opyt* (2019)
6. Ekzoskelety – eto novaya neobhodimost'. Pochemu rossijskoj promyshlennosti pridetsya ih ispol'zovat'? https://vc.ru
7. Yu. S. Vanyushin, R. R. Hajrullin, TiPFK 7 (2015)
8. P. Maurice, J. Čamernik, D. Gorjan, B. Schirrmeister, J. Bornmann, L. Tagliapietra, C. Latella, D. Pucci et al., IEEE Transactions on Neural Systems and Rehabilitation Engineering **28(1)**, 152–164 (2020)
9. M. Grimmer, B. T. Quinlivan, S. Lee, P. Malcolm, D. M. Rossi, C. Siviy, C. J. Walsh, Journal of Biomechanics **83(23)**, 76–84 (2019)
10. T. Bosch, J. Eck, K. Knitel, M. Looze, Applied Ergonomics 54, 212–217 (2016)

11. J. Masood, A. Dacal-Nieto, V. Alonso-Ramos, M. I. Fontano, A. Voilqué, J. Bou, Industrial Wearable Exoskeletons and Exosuits Assessment Process. Wearable Robotics: Challenges and Trends **22**, 234–238
12. G. Chen, J. Wu, G. Chen, Y. Lu, W. Ren, W. Xu, X. Xu, Z. Wu et al., PLoS ONE **14(7)** (2019)
13. A. S. Yacun, Ya. S. Nikulin, E. R. Logunov, Zavalishinskie chteniya **23**, 149-154 (2023)
14. A. S. Yacun et al., “Primenenie myagkogo ekzoskeleta pri vypolnenii rabot na strojploshchadke”, in *Mekhanizaciya i avtomatizaciya stroitel'stva* (2020)
15. W. L. A. Lo, Q. Yu, Y. Mao, W. Li, Ch. Hu, L. Li, BMC Musculoskelet Disord **23(20 (1))**, 559 (2019)
16. S. F. Yacun et al., *Ekzoskelety: analiz konstrukcij, klassifikacii, principy sozdaniya, osnovy modelirovaniya* (2014)
17. S. F. Yacun et al., *Ekzoskelety: analiz konstrukcij, principy sozdaniya, osnovy modelirovaniya* (2015)
18. Callibri Muscle Tracker, https://callibri.com/ru/callibri-muscle-tracker
19. Oficial'nyj sajt proizvoditelya, https://kernel.nt-rt.ru/
20. R. Samusev Anatomiya cheloveka (Litres, 2022)
21. Shirochajshaya myshca spiny, https://physiotherapist.ru/muscles/latissimus-dorsi-muscle
22. A. P. Shein, G. A. Krivoruchko, Chelovek. Sport. Medicina **4(44)** (2005)
23. Tekhnicheskie priemy i rabochie metody pod"ema i peremeshcheniya tyazhestej, https://labor-safety.org/blog/
24. GOST R. 11228-1-2009 Ruchnaya obrabotka gruzov. Podnyatie i perenoska. Obshchie trebovaniya (2009)
25. R 2.2.2006-05. 2.2. Gigiena truda. Rukovodstvo po gigienicheskoj ocenke faktorov rabochej sredy i trudovogo processa. Kriterii i klassifikaciya uslovij truda>5. Gigienicheskie kriterii i klassifikaciya uslovij truda pri vozdejstvii faktorov rabochej sredy i trudovogo processa 5.10. Tyazhest' i napryazhennost' trudovogo processa (2006)