UDC 621.865.8

DESIGN AND OPTIMIZATION OF WEARABLE ACTIVE WAIST AND LEG EXOSKELETON STRUCTURE FOR MINING

Qing Chen[1,3], Tianhong Luo[2], Alexey Khoreshok[1], Kirill Varnavskiy[1], Alexander Ermakov[1], Qihang Zeng[3], Tao Xi[1,3], Guangyong Wu[1,3]

[1] T.F. Gorbachev Kuzbass State Technical University
[2] Chongqing City Vocational College
[3] Chongqing University of Arts and Sciences

Information about article
Received:
22 January 2024

Reviewed:
12 March 2024

Accepted:
25 March 2024

Keywords:
Exoskeleton for Mining; Structural Design; Topology Optimization; Lightweight Design, Finite Element Analysis

Abstract.
In response to the high labor intensity of manual operations in coal mines, an exoskeleton was developed to assist miners in transporting and carrying heavy tools or materials in underground mining workings. The structural design and functions of each part of the exoskeleton were introduced. By using finite element analysis technology, the equivalent stress and displacement distribution law of the core components of waist and leg exoskeleton under working conditions were obtained. Based on this, combined with topology optimization technology and technological characteristics of manufacturing process, the optimal structural scheme of the components was obtained. Finally, a lightweight design with a total weight of 8.3 kg (23.1% decreasing of weight compared to the original design) was developed for the waist and leg exoskeleton, providing a solid foundation for the application of exoskeletons in conditions of coal mine.

For citation: Chen Q., Luo T., Khoreshok A., Varnavsky K., Ermakov A., Zeng Q., Xi T., Wu G. Design and optimization of wearable active waist and leg exoskeleton structure for. *Journal of mining and geotechnical engineering*, 1(24):43. DOI: 10.26730/2618-7434-2024-1-43-57, EDN: HSNZBX

Introduction

With the advancement of coal mining technology, underground work is developing towards mechanization and automation. Ensuring industrial safety and labor protection of workers is one of the priorities of a mining enterprise, since mining is a complex and dangerous process associated with the risk of accidents and occupational diseases [1]. The application of mining exoskeleton provides strong support for miners, enabling them to easily move heavy objects and perform wide range of tasks with increased physical exertion. The application of this mechanical device improves the physical fitness of operators in specific aspects such as load-bearing capacity and walking durability, while also improving the overall production efficiency of coal mining. Exoskeleton equipment is a type of equipment that combines mechanical structure and intelligent control technology [2]. The exoskeleton is worn on the body completely repeating the structure of the body, providing auxiliary strength and protection for the human body [3, 4].

Exoskeleton have been widely studied in various application fields. The HULC exoskeleton developed in collaboration between Martin Corporation and the University of Berkeley in the United States adopts hydraulic transmission, which can assist the human body in weight-bearing walking and complete movements such as crawling and squatting [5]. Professor Luo Jinfa from Singapore has developed a lower limb exoskeleton, which is driven by an electric motor and provides assistance by measuring joint angles through sensors on the inner exoskeleton [6].

S. Toyama, G. Yamamoto et al. [7-10] have developed an agricultural version of exoskeleton to reduce the labor intensity of farmers.

The University of Tsukuba has developed the HAL series of exoskeleton to assist the movements of the elderly and disabled [11].

Shanghai Fourier Intelligent Technology Co., Ltd., a domestic company, has developed the Fourier X1 series exoskeleton, which can help paralyzed patients achieve functions such as walking. Li Xiankun et al. [12, 13] developed a lower limb exoskeleton experimental platform and studied the movement characteristics of the exoskeleton during squatting. Zhang Bin et al. [14] developed an exoskeleton for rehabilitation training and analyzed the characteristics of the control system.

Developed by Russian scientists at The South-West State University (SWSU), exoskeletons minimally limit the operator's movement in space and help relieve stress from the lower back. With the support of industrial partners of SWSU on the implementation of heavy-duty industrial exoskeletons, cases were carried out to evaluate the range of possibilities for using exoskeletons. The results of tests of exoskeletons of this type showed that heavy exoskeletons «ExoHeaver» make it possible to perform such technological operations as: the operation of lifting, transferring and installing a valve weighing 40 kg on a worktable; lifting, moving, holding a load; assembly of units and units of medium dimensions. By removing the load from the musculoskeletal system, operator relief exceeds 90%, and the operating weight range when putting on an industrial exoskeleton ranges from 30 to 60 kg [15, 16].

At present, there are three obvious problems with active exoskeletons used in mining: their volume and weight are too large (the existing machine weight is ≥ 11kg), and wearing them on workers in small space mining environments can have a great sense of constraint; The existing exoskeletons have poor degrees of freedom and limit the flexibility of the human torso too much; Carrying exoskeletons, transporting exoskeletons, and assisting with walking exoskeletons each have three sets of systems. However, mining work often involves multiple continuous actions, and one set of exoskeletons cannot adapt to diverse mine conditions, resulting in relatively single functions. Therefore, it is imperative to develop lightweight and wearable exoskeleton robots for mining in the field of coal mining.

Structural design of mining waist and leg exoskeleton

Design of degrees of freedom

Many foreign researchers believe that exoskeletons have characteristics similar to those of personal protection. Experts recognize that the features of these devices, including the processes of donning, fixing, fitting and adjustment carried out directly on the human body, allow them to be considered personal protective equipment. ASTM Committee F48 on Exoskeletons and Exosuits, which develops standards for exoskeletons and exosuits, noted at one of its meetings that exoskeletons represent a new type of personal protective equipment. By reducing the load on joints and muscles, exoskeletons can function as smart personal protective equipment, protecting the worker from the rigors of the work process, or as a means of increasing labor productivity [17].

Normal human walking relies on the coordinated movement of the hip, knee, and ankle joints. The human lower limbs have a total of 7 degrees of freedom, with the hip and ankle joints each responsible for 3 degrees of freedom, including flexion/extension, abduction/adduction, and pronation/pronation movements around the joint motion axis. The knee joint has only one degree of freedom, which is the flexion/extension movement around the joint's axis of motion. Among them, flexion/extension movements are mainly used to bend and extend the lower limbs, playing a role in bending and extending the legs, allowing the human body to take strides. The abduction/adduction movement is used to regulate the balance of the human body and maintain stability during walking. Internal/external rotation can achieve the function of changing direction during walking.

The design of the hip joint shown in Fig. 1 can achieve the three degrees of freedom required for the human hip joint.

DOI: 10.26730/2618-7434-2024-1-43-57

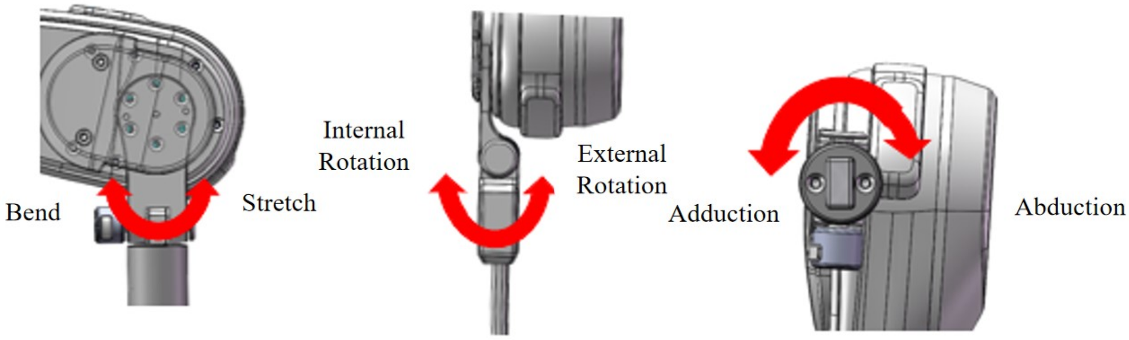


Fig. 1. Hip joint 3-degree-of-freedom design
Рис. 1. Конструкция тазобедренного сустава с 3 степенями свободы

The ankle joint design shown in Fig. 2 can achieve the three degrees of freedom required for the human ankle joint.

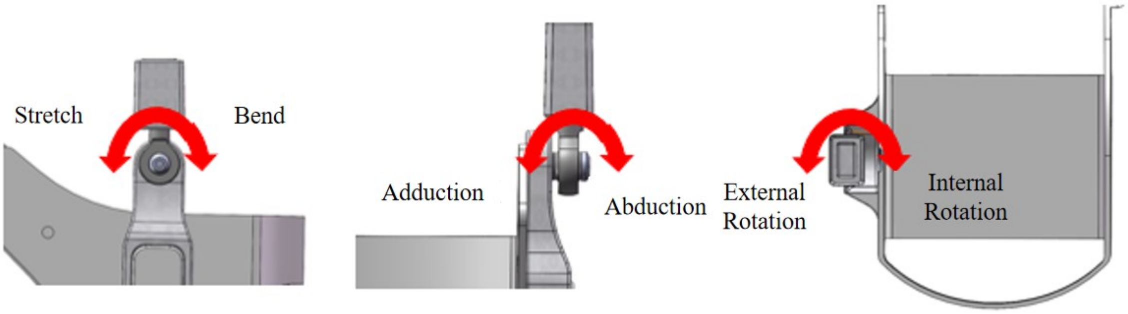


Fig. 2. Ankle joint 3-degree-of-freedom design
Рис. 2. Конструкция соединительного компонента на голени с 3 степенями свободы

The knee joint design shown in Fig. 3 can achieve one degree of freedom required for the human knee joint.

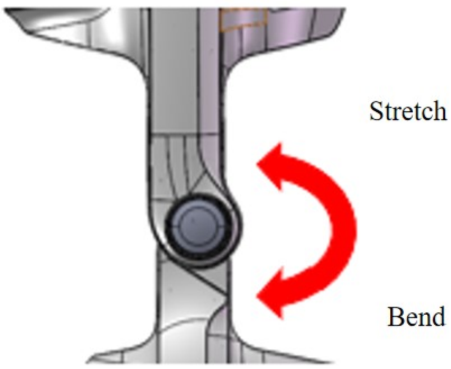


Fig. 3. Knee joint 1 degree of freedom design
Рис. 3. Конструкция коленного сустава с 1 степенью свободы

Design of driving mode

Research has shown that during normal walking in the human body, the hip and knee joints consume the most energy, and the hip joint is larger than the knee joint. That is to say, in the actual work of coal mine workers, the flexion/extension direction of the hip joint is the direction with the maximum resistance distance [18]. Therefore, in the design process of exoskeletons, the Fig. 4 shows the design of the driver for the waist and leg exoskeleton, with one motor on each side.

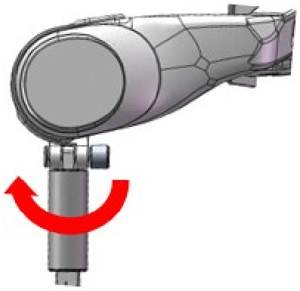


Fig. 4. Design of degrees of freedom for motor drive
Рис. 4. Конструкция исполнительного привода (электропривода) с несколькими степенями свободы

Structural and Mechanical Analysis of Waist and Leg Exoskeleton Machine

Underground operations usually include two categories: (1) tasks such as moving heavy objects, climbing slopes, and walking; (2) carrying injured personnel, equipment, etc. during emergency rescue; In order to better cooperate with the coal mine environment operation scene, this article designs two types of exoskeletons: the waist handling exoskeleton shown in Fig. 5, and the leg assisted exoskeleton shown in Fig. 6. Both types of exoskeletons can be quickly disassembled through special structures, collectively referred to as the waist leg exoskeleton in this article.

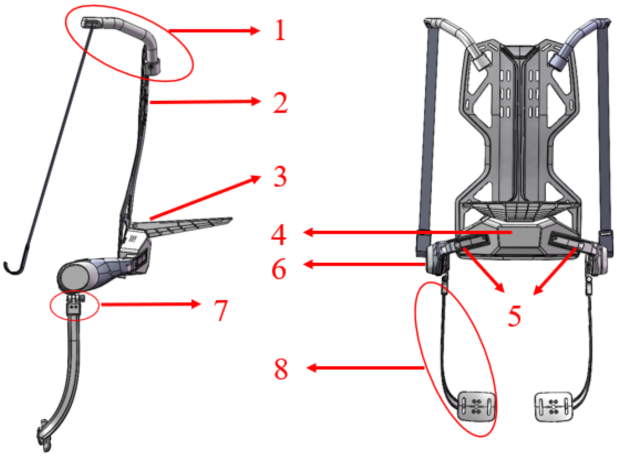


Fig. 5. Waist handling exoskeleton. 1 – Arm suspension system, 2 – Body simulation backboard, 3 – Bracket, 4 – Electric control and its battery system, 5 – Hip joint adjustment system, 6 – Motor drive system, 7 – Waist and leg quick change mechanism, 8 – Leg binding components
Рис. 5. Экзоскелет верхних конечностей. 1 – система подвески рычага, 2 – панель для поддержки спины, 3 – скоба, 4 – контрольно-измерительная система и ее блок питания, 5 – система регулировки тазобедренного сустава, 6 – исполнительный привод (электрический привод), 7 – механизм быстрой смены элемента крепления ноги с пояса, 8 – элемент крепления ноги

The exoskeleton for waist transportation consists of 8 modules, including 1 – prosthetic arm suspension system, 2 – simulated body backboard, 3 – bracket components, 4 – electronic control and battery system, 5 – hip joint adjustment system, 6 – motor drive system, 7 – waist leg quick change mechanism, and 8 – leg binding components. When coal mine operators bend down to carry lighter heavy objects, they can place the heavy objects on the gripper of the prosthetic arm suspension system as shown in Fig. 7. At this time, when bending down to carry heavy objects, most of the force for lifting them is achieved by the reverse drive torque T of the motor, as shown in Fig. 7, which can greatly alleviate waist fatigue in the human body. When coal mine workers are carrying a lighter load, they can place heavy objects on a bracket, as shown in Fig. 8. During walking, the motor driving torque T can drive the human thigh to swing, thereby alleviating leg fatigue and improving the work efficiency of coal mine workers.

DOI: 10.26730/2618-7434-2024-1-43-57

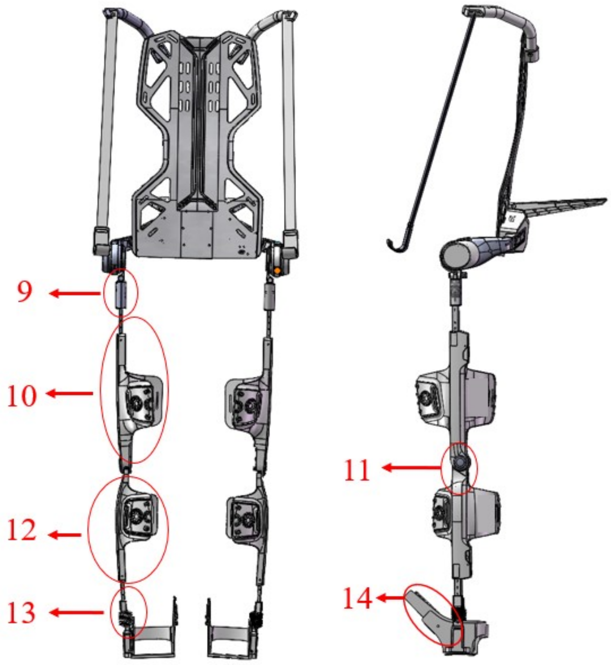


Fig. 6. Waist and leg exoskeleton. 9 – Hip shock absorption system, 10 – Thigh binding component, 11 – Knee joint system, 12 – Lower leg binding components, 13 – Ankle joint system, 14 – Shoe system

Рис. 6. Экзоскелет нижних конечностей. 9 – система амортизации бедра, 10 – бедренный соединительный компонент, 11 – система коленного сустава, 12 – голеностопный соеденительный компонент, 13 – система голеностопного сустава, 14 – система крепления

Fig. 7. Experimental measurement and force transmission diagram of the lumbar exoskeleton prosthetic arm for transporting heavy objects: ①– Shoulders, ②– Back, ③–Waist, ④– Legs

Рис. 7. Эксперементальные измерения и схема передачи услия поясничного экзоскелета, оснащенного поддержкой для рук, для транспортировки тяжелых предметов: ①– плечи, ②– спина, ③– талия, ④– ноги

DOI: 10.26730/2618-7434-2024-1-43-57

Fig. 8. Measurement and force transmission diagram of the load on the lumbar exoskeleton backboard

Рис. 8. Схема измерения и передачи усилия на заднюю панель поясничного экзоскелета

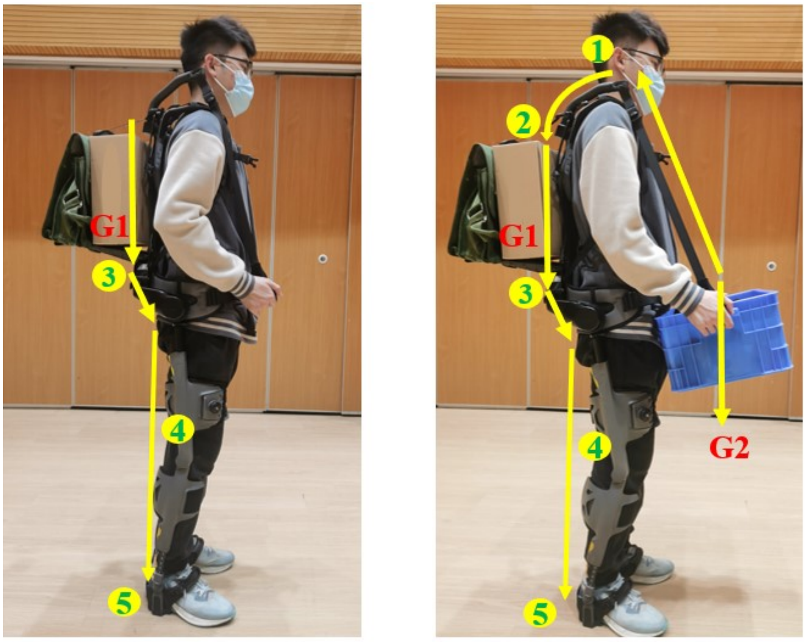


Fig. 9. Actual measurement and force transmission schematic diagram of the waist and leg exoskeleton carrying and transporting heavy objects: ① – Shoulders, ② – Back, ③ – Waist, ④ – Legs, ⑤ – Ground

Рис. 9. Фактическое измерение и схема передачи усилия экзоскелета нижних конечностей для транспортировки тяжелых предметов: ① – плечи, ② – спина, ③ – талия, ④ – ноги, ⑤ – стопа

When coal mine operators carry or transport heavy loads (greater than or equal to 25 kg), they can place the heavy object on a bracket or gripper, as shown in Fig. 9. The force transmission diagram is shown in the figure, and the load weight G1 (or G2) is transmitted to the ground through the structure of the exoskeleton. During the process of carrying or transporting, it can greatly reduce the burden on the human body while assisting in walking.

In addition, the overall structure of the machine adopts 7075 aluminum alloy, carbon fiber, nylon+glass fiber composite plastic, which reduces the weight of the waist and leg exoskeleton while maintaining overall stiffness; In order to match people of different heights, the hip width and leg length of the exoskeleton in this article can be adjusted and matched. At the same time, it can ensure that the human knee joint and the exoskeleton knee joint are at the same height when wearing and using and make the joint rotation axis of the exoskeleton coincide with the human joint axis as much as possible, increasing the compatibility and comfort of the exoskeleton.

Structural optimization

Although the overall weight of the active waist and leg exoskeleton has been reduced to 10.2kg through reasonable material selection, the use of exoskeletons in coal mining environments is not yet the most solution. Therefore, this article uses topology optimization technology and combines the characteristics of later mass production processes (injection molding, die-casting, machining, etc.) to obtain the optimal structural scheme of the components in advance, while ensuring that the maximum equivalent stress and maximum displacement meet the requirements, Further weight reduction of active waist and leg exoskeletons in mechanical structure.

This article takes one of the core components, the thigh baffle, as an example to use topology optimization technology for lightweight design of the thigh baffle. The specific process is shown in Fig. 10.

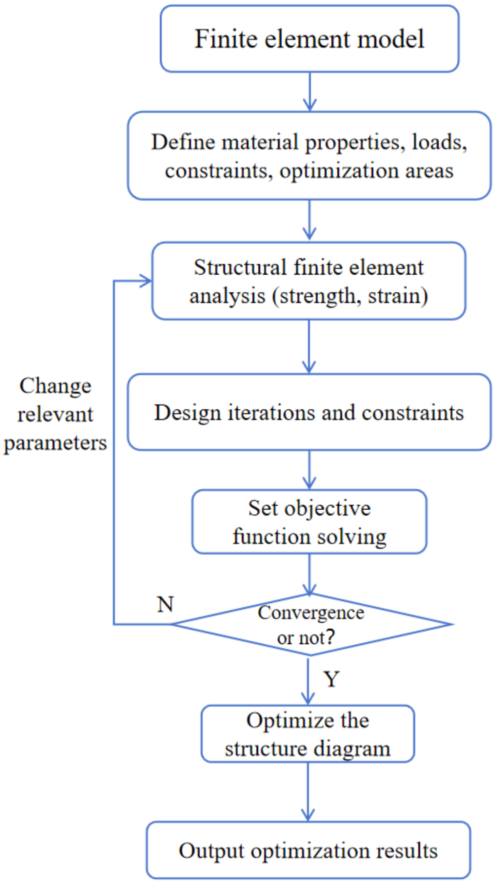


Fig. 10. Topology optimization process diagram of thigh baffle
Рис. 10. Схема процесса оптимизации топологии перегородки бедра

Finite element analysis

The first choice is to conduct strength analysis on the original structure of the thigh baffle. The material used for the thigh baffle in this article is PA+30% GF. The loading was applied in Workbench according to the actual working conditions, and the equivalent stress-strain values were obtained as shown in Fig. 11. It is easy to find that the stress and deformation 0.31 mm experienced by the thigh baffle in many areas are much smaller than the actual allowable figure (the maximum allowable stress is 80MPA, and the maximum allowable radial displacement is 0.5 mm), So, under the conditions of meeting strength and deformation, the material in this area of the thigh baffle can be removed to obtain an optimized baffle structure.

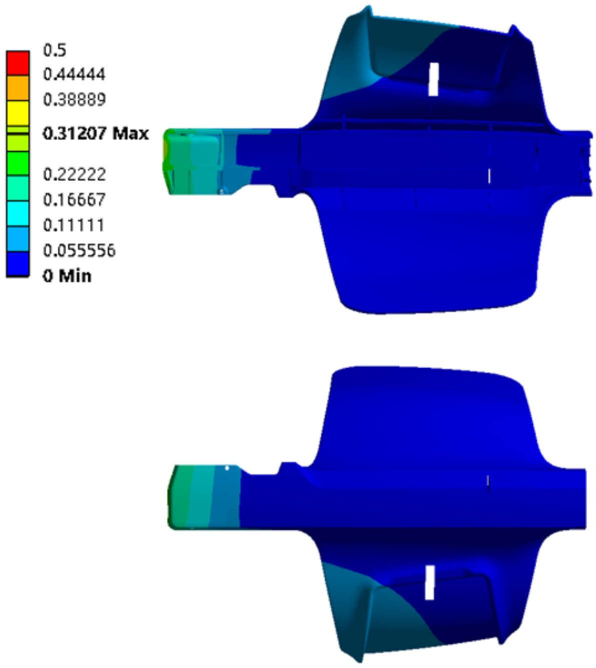


Fig. 11. Equivalent Stress Diagram and Equivalent Deformation Diagram of Thigh Shield
Рис. 11. Диаграмма эквивалентных напряжений и диаграмма эквивалентной деформации перегородки бедра

Optimization of topology

The topology optimization of the thigh baffle in this section is based on its strength analysis, which involves removing materials from specific areas while ensuring the structural strength of the baffle. The specific processing and analysis process consist the following steps:

Firstly, pre-processing optimization is carried out. The correct application of loads and constraints has a direct impact on the optimization results. Import the thigh guard model into Workbench, set the material properties, and ensure that the loading of guard boundary conditions and related loads are consistent with those in the strength analysis. At the same time, during the mesh division in Workbench Meshing, an intelligent mesh is still used in combination with subdivision at specific locations. As seen in the equivalent stress diagram (Fig.11), the stress and strain in region 1 are relatively high and approaching the critical value, while the stress values in region 2 are lower and the safety is greater. Therefore, region 2 is selected as the focus for key optimization, as shown in the following Fig.12. The blue part represents the optimization area, with the remaining parts being the frozen area that does not participate in topology optimization.

Then, set the constraint conditions. Based on the actual assembly conditions, the maximum deformation of the thigh guard's main structure must not exceed 0.5mm, otherwise it may cause motion wear or interference, hence the displacement constraint condition is $s(x) \leq 0.5$mm. Moreover, the material PA 30% gf has a yield limit of approximately $\sigma s = 180$MPa at room temperature. With a safety factor of 2, the strength constraint condition is set so that the stress experienced by the guard, $\sigma(x)$, should not exceed $\sigma s/2 \approx 90$ MPa.

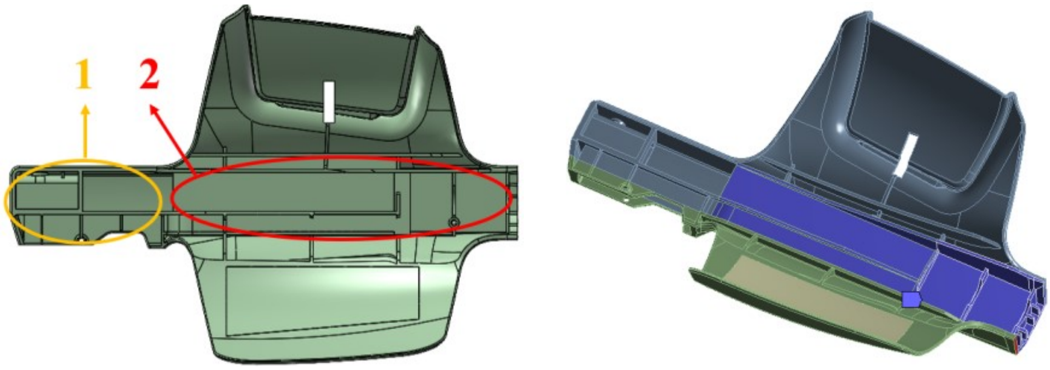


Fig. 12. Defines the blue area as the optimization region
Рис. 12. Определение синей области как области оптимизации

Once again, set the target amount for optimization. The original weight of the model is 0.265kg, and based on multiple iterations of experience, the remaining material percentage is set to 75%, that is, the deleted material percentage is 25%. After 33 automatic iterations, topology optimization operations were completed. The final result of topology optimization is shown in Fig. 13, with the red part indicating the removable materials.

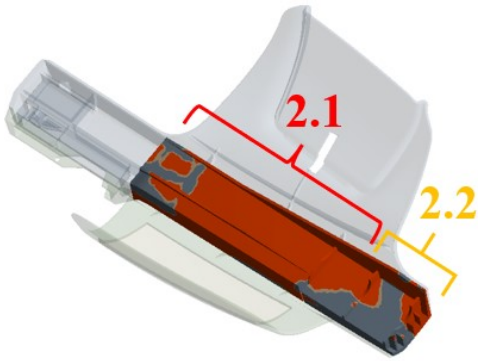


Fig. 13. Topology optimization results of thigh baffle
Рис. 13. Результаты оптимизации топологии перегородки бедра

Finally, regarding the topology optimization results and analysis. When meeting the strength constraint stress σ (x) Under the conditions of ≤ 90 MPa and s (x) ≤ 0.5 mm, it can be clearly seen that the optimized structure has extremely irregular shapes and unclear boundaries, indicating poor manufacturability of the structure after topology optimization; However, the results of topology optimization can serve as an important design reference. This part, combined with the injection molding manufacturing process used in later mass production, has been improved in the design of the thigh baffle: ① According to the injection molding process, the wall thickness of region 2.1 (almost all red area) has been normalized (equal wall thickness of 3mm); ② While normalizing the wall thickness in region 2.2 (partially red) (with an equal wall thickness of 3mm), add 0.8 mm reinforcement bars in both longitudinal and transverse directions to increase its strength; ③ All transition parts are rounded. Based on the above three points, rebuild the 3D model in Solidworks as shown in Fig. 14.

Perform strength simulation analysis and verification on the optimized structural scheme, as shown in Fig. 14 σ (x) =79 MPa ≤ 90 MPa = σ (allowable), s (x) = 0.48 mm ≤ 0.5 mm. The data is summarized in Table 1. It can be seen that, while ensuring that the maximum equivalent stress and maximum radial displacement meet the requirements in advance, the weight of the new structure of the thigh baffle has been reduced by about 27.17%, achieving the optimization goal of lightweight.

The other structural components of the active waist leg exoskeleton also achieved a weight reduction of 27.2% on individual parts by combining the topology optimization and actual process described above; ultimately, the weight of the entire machine was reduced from 10.8 kg to 8.3 kg, with a weight reduction of 23.1%.

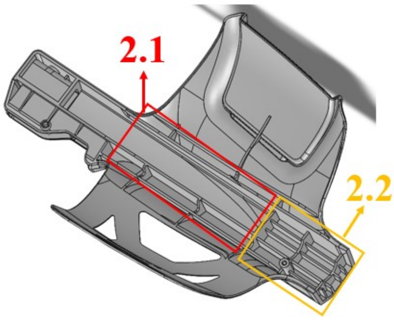
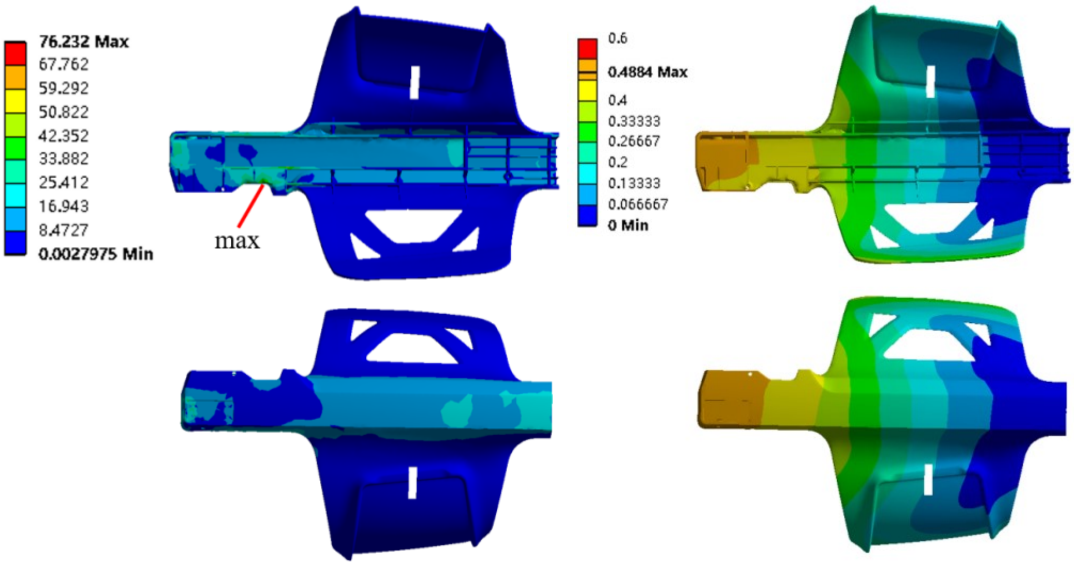


Fig. 14. Baffle model after structural optimization
Рис. 14. Модель перегородки после структурной оптимизации



Equivalent Stress Diagram (in MPa) *Deformation Diagram (in cm)*
Fig. 15. Equivalent stress diagram and deformation diagram of optimized thigh baffle
Рис. 15. Эквивалентная диаграмма напряжений и диаграмма деформаций оптимизированной перегородки бедра

Table 1. Comparison between the final solution and the original model
Таблица 1. Сравнение полученного результата с исходным вариантом

Programme	Baffle quality (kg)	Maximum equivalent stress (MPa)	Maximum deformation (mm)
Original	0.265	45.173	0.312
Optimization	0.193	76.232	0.488
Contrast	Lose weight 27.2%	All meet the requirements	All meet the requirements

Conclusion

Based on the scenarios of rescue, rapid evacuation, and auxiliary transportation in coal mines, this paper designs and develops an ultra-lightweight active waist and leg exoskeleton. By comparing the overall weight and maximum equivalent stress parameters before and after optimization, the feasibility of the structural optimization scheme is verified. The main conclusions are as follows:

(1) Using topology optimization technology combined with existing processes to reduce the weight of the exoskeleton machine to 8.3 kg, greatly solving the problem of strong constraint and binding of the exoskeleton worn by underground workers;

(2) By combining the biomimetic structural design of hip, knee, ankle and other joints with the aforementioned lightweight processing, the problem of flexibility in trunk movement is solved;

(3) In response to the special needs of mining conditions, through modular design methods, we innovatively integrate three functions of carrying, transporting, and assisting in movement into a set of exoskeletons, and can achieve free switching of the exoskeleton system between three scenarios, better matching the actual needs of underground workers.

Conflicts of Interest

The authors declare no conflict of interest.

Funding: This research was supported by grant of the Natural Science Foundation of Chongqing (No. cstc2021jcyj-msxmX0812) – sections 1, 3, 4, and by a state assignment of the Ministry of Science and Higher Education of the Russian Federation (No. 075–03-2024-082-2) – sections 1, 2.

Information about the authors

Qing Chen, post graduate student at Mining Institute of T.F. Gorbachev Kuzbass State Technical University, Senior Lecture of College of Intelligent Manufacturing Engineering of Chongqing University of Arts and Sciences
e-mail: 1072296534@qq.com
T.F. Gorbachev Kuzbass State Technical University. 28 Vesennyaya str., Russian Federation, Kemerovo, 650000
Chongqing University of Arts and Sciences
319 Honghe Avenue, Yongchuan District, Chongqing, PR China, 402171

Tianhong Luo, PhD, Professor, Head of Chongqing City Vocational College.
e-mail: 63077600@qq.com
1099 Xinglong Avenue, Yongchuan District, Chongqing, PR China, 401331

Alexey A. Khoreshok, Doctor of Technical Science, Professor, Principal Investigator of Mining Institute
e-mail: haa.omit@kuzstu.ru

Kirill A. Varnavskiy, PhD, Head of the Research Laboratory of Mining Industry Digitalization
e-mail: varnavskijka@kuzstu.ru

Alexander N. Ermakov, PhD (Tech.), Associate Professor, Head of Mining Institute
e-mail: ermakovan@kuzstu.ru
T.F. Gorbachev Kuzbass State Technical University. 28 Vesennyaya str., Russian Federation, Kemerovo, 650000

Qihang Zeng, PhD, Senior Lecture of College of Intelligent Manufacturing Engineering of Chongqing University of Arts and Sciences.
e-mail: zqh0823@foxmail.com
Chongqing University of Arts and Sciences. 319 Honghe Avenue, Yongchuan District, Chongqing, PR China, 402171

Tao Xi, post graduate student at Mining Institute of T.F. Gorbachev Kuzbass State Technical University, Senior Lecture of College of Intelligent Manufacturing Engineering of Chongqing University of Arts and Sciences.
e-mail: 419926008@qq.com

Guangyong Wu, post graduate student at Mining Institute of T.F. Gorbachev Kuzbass State Technical University, Senior Lecture of College of Intelligent Manufacturing Engineering of Chongqing University of Arts and Sciences.
e-mail: 93417197@qq.com

T.F. Gorbachev Kuzbass State Technical University. 28 Vesennyaya str., Russian Federation, Kemerovo, 650000

Chongqing University of Arts and Sciences. 319 Honghe Avenue, Yongchuan District, Chongqing, PR China, 402171

References

1. Smagina, S.S. Management of labor protection and industrial safety at coal mining enterprises of Kuzbass / S. S. Smagina, O. V. Kadnikova, A. A. Rolgaiser // Labor Economics. – 2018. – No. 2 (5). – pp. 541–554. DOI: 10.18334/et.5.2.39141.
2. Guo, K. Research on linear quadratic optimal control in vibration control of flexible manipulator / K. Guo, G. Liu, Q. Wang. Machinery Design & Manufacture. – 2018. – No. 7. – pp. 256-259.
3. Wang Jicai, Sun Xianjie, Liu Ruozhu, etc. Design and study of the structural drive system of the human weight-bearing exoskeleton. Hydraulic and Pneumatic, 2018, (4): 49-53.
4. Hensel, R, Keil, M. Subjective Evaluation of a Passive Industrial Exoskeleton for Lower Back Support: A Field Study in the Automotive Sector. IISE Transactions on Occupational Ergonomics and Human Factors, 2019, (7), 3-4.
5. Juan C. Analysis of the Human Interaction with a Wearable Lower-limb Exoskeleton. Applied Bionics & Biomechanics, 2014, 6(2): 245-256.
6. Gilwhoan C, Jincheol H. The Experiments of Wearable Robot for Carrying Heavy-weight Objects of Shipbuilding Works. 2014 IEEE International Conference on Automation Science and Engineering, Taipei, Taiwan, 2014: 978-983.
7. Kawale S S, Sreekumar M. Design of a Wearable Lower Body Exoskeleton Mechanism for Shipbuilding Industry. Procedia Computer Science, 2018, 7(4): 133-135.
8. Toyama S, Yamamoto G. Development of Wearable-agri-robot Mechanism for Agricultural Work. 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, St. Louis, USA, 2009: 5801-5806.
9. Luger T, Seibt R, Cobb T J, et al. Influence of a Passive Lower-limb Exoskeleton During Simulated Industrial Work Tasks on Physical Load, Upper Body Posture, Postural Control and Discomfort. Applied Ergonomics, 2019, 6(8): 80-82.
10. Niu J.K., Song Q.Z., Wang X.G. Fuzzy PID Control for Passive Lower Extremity Exoskeleton in Swing Phase. IEEE International Conference on Electronics Information and Emergency Communication, Beijing, China: IEEE, 2013: 185-188.
11. Li Xiankun, Liu Fang, Chi Zhenhua, et al. Study on kinematics of motion-driven hydraulic cylinder with power-assisted exoskeleton based on ADAMS. Modern Manufacturing Engineering, 2014, (8): 32-36.
12. The hybrid assistive limb (HAL) for Care Support successfully reduced lumbar load in repetitive lifting movements / Miura K, [et al.] // Clin Neurosci. – 2018. – No. 6(53). – pp. 276-279. DOI: 10.1016/j.jocn.2018.04.057.
13. Zhang Bin, Liu Fang, Yang Xiaoping, et al. Study on the characteristic action dynamics of wearable assisted exoskeleton // Mechanical design and manufacturing, 2018, (8): 142-145.
14. Experience in the use of industrial exoskeletons at mining enterprises / A. S. Yatsun, A. A. Postolny, E. V. Savelyeva, Ya. S. Nikulin // Extreme Robotics. – 2021. – No. 1 (32). – pp. 245–250.
15. Yatsun, A. Efficiency Investigation of the Exoskeleton Control Systems with Linear Gravity Compensator / A. Yatsun, A. Karlov, S. Yatsun // 2020 IEEE International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon). – 2020. DOI: 10.1109/FarEastCon50210.2020.9271317.
16. Industrial exoskeletons as a means of ensuring industrial safety. Normative and technical regulation / I. V. Bukhtiyarov, A. M. Geregey, A. R. Efimov, E. V. Kostyleva // Labor safety in industry. – 2020. – No. 12. – P. 53–57. DOI: 10.24000/0409-2961-2020-12-53-57.
17. Andrew Chun, H. Kazerooni, Adam Zoss. On the Biomimetic Design of the Berkeley lower Extremity Exoskeleton (BLEEX). Proceedings of the 2005 lEEE International Conference on Robotics and Automation, Barcelona, Spain, 2005.

РАЗРАБОТКА И ОПТИМИЗАЦИЯ КОНСТРУКЦИИ КАРКАСНОГО АКТИВНОГО ЭКЗОСКЕЛЕТА НИЖНИХ КОНЕЧНОСТЕЙ ДЛЯ ГОРНЫХ РАБОТ

Цин Чень[1,3], Тяньхун Ло[2], Хорешок А.А.[1], Варнавский К.А.[1], Ермаков А.Н.[1], Цихан Цзэн[3], Тао Си[1,3], Гуанъюн У[1,3]

[1] Кузбасский государственный технический университет имени Т.Ф. Горбачева
[2] Чунцинский городской профессиональный колледж
[3] Чунцинский университет искусств и науки

Информация о статье
Поступила:
22 января 2024 г.

Рецензирование:
12 марта 2024 г.

Принята к печати:
25 марта 2024 г.

Ключевые слова: экзоскелет для горной промышленности; конструкция; оптимизация топологии; облегченная конструкция, метод конечных элементов

Аннотация.
В связи с наличием ручных операций на угольных шахтах, сопряженных с большой физической нагрузкой, был разработан экзоскелет, помогающий рабочим транспортировать и переносить тяжелые инструменты или материалы в подземных горных выработках. Были представлены конструкция и функции каждой части экзоскелета. С помощью технологии конечно-элементного анализа был получен эквивалентный закон распределения напряжений и смещений основных компонентов экзоскелета нижних конечностей в рабочих условиях. На основе этого в сочетании с технологией оптимизации топологии и технологических характеристик производственного процесса получена оптимальная структурная схема компонентов. Наконец, для экзоскелета пояса и ног была разработана облегченная конструкция общим весом 8,3 кг (снижение веса на 23,1% по сравнению с исходной конструкцией), обеспечивающая потенциальный задел для применения экзоскелетов в условиях угольных шахт.

Для цитирования: Чень Ц., Ло Т., Хорешок А., Варнавский К., Ермаков А., Цзэн Ц., Си Т., У Г. Разработка и оптимизация конструкции каркасного активного экзоскелета нижних конечностей для горных работ // *Техника и технология горного дела*, 1(24):43. DOI: 10.26730/2618-7434-2024-1-43-57, EDN: HSNZBX

References

1. Smagina, S.S. Management of labor protection and industrial safety at coal mining enterprises of Kuzbass / S. S. Smagina, O. V. Kadnikova, A. A. Rolgaiser // Labor Economics. – 2018. – No. 2 (5). – pp. 541–554. DOI: 10.18334/et.5.2.39141.
2. Guo, K. Research on linear quadratic optimal control in vibration control of flexible manipulator / K. Guo, G. Liu, Q. Wang. Machinery Design & Manufacture. – 2018. – No. 7. – pp. 256-259.
3. Wang Jicai, Sun Xianjie, Liu Ruozhu, etc. Design and study of the structural drive system of the human weight-bearing exoskeleton. Hydraulic and Pneumatic, 2018, (4): 49-53.
4. Hensel, R, Keil, M. Subjective Evaluation of a Passive Industrial Exoskeleton for Lower Back Support: A Field Study in the Automotive Sector. IISE Transactions on Occupational Ergonomics and Human Factors, 2019, (7), 3-4.
5. Juan C. Analysis of the Human Interaction with a Wearable Lower-limb Exoskeleton. Applied Bionics & Biomechanics, 2014, 6(2): 245-256.
6. Gilwhoan C, Jincheol H. The Experiments of Wearable Robot for Carrying Heavy-weight Objects of Shipbuilding Works. 2014 IEEE International Conference on Automation Science and Engineering, Taipei, Taiwan, 2014: 978-983.
7. Kawale S S, Sreekumar M. Design of a Wearable Lower Body Exoskeleton Mechanism for Shipbuilding Industry. Procedia Computer Science, 2018, 7(4): 133-135.
8. Toyama S, Yamamoto G. Development of Wearable-agri-robot Mechanism for Agricultural Work. 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, St. Louis, USA, 2009: 5801-5806.
9. Luger T, Seibt R, Cobb T J, et al. Influence of a Passive Lower-limb Exoskeleton During Simulated Industrial Work Tasks on Physical Load, Upper Body Posture, Postural Control and Discomfort. Applied Ergonomics, 2019, 6(8): 80-82.
10. Niu J.K., Song Q.Z., Wang X.G. Fuzzy PID Control for Passive Lower Extremity Exoskeleton in Swing Phase. IEEE International Conference on Electronics Information and Emergency Communication, Beijing, China: IEEE, 2013: 185-188.
11. Li Xiankun, Liu Fang, Chi Zhenhua, et al. Study on kinematics of motion-driven hydraulic cylinder with power-assisted exoskeleton based on ADAMS. Modern Manufacturing Engineering, 2014, (8): 32-36.

12. The hybrid assistive limb (HAL) for Care Support successfully reduced lumbar load in repetitive lifting movements / Miura K, [et al.] // Clin Neurosci. – 2018. – No. 6(53). – pp. 276-279. DOI: 10.1016/j.jocn.2018.04.057.
13. Zhang Bin, Liu Fang, Yang Xiaoping, et al. Study on the characteristic action dynamics of wearable assisted exoskeleton // Mechanical design and manufacturing, 2018, (8): 142-145.
14. Experience in the use of industrial exoskeletons at mining enterprises / A. S. Yatsun, A. A. Postolny, E. V. Savelyeva, Ya. S. Nikulin // Extreme Robotics. – 2021. – No. 1 (32). – pp. 245–250.
15. Yatsun, A. Efficiency Investigation of the Exoskeleton Control Systems with Linear Gravity Compensator / A. Yatsun, A. Karlov, S. Yatsun // 2020 IEEE International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon). – 2020. DOI: 10.1109/FarEastCon50210.2020.9271317.
16. Industrial exoskeletons as a means of ensuring industrial safety. Normative and technical regulation / I. V. Bukhtiyarov, A. M. Geregey, A. R. Efimov, E. V. Kostyleva // Labor safety in industry. – 2020. – No. 12. – P. 53–57. DOI: 10.24000/0409-2961-2020-12-53-57.
17. Andrew Chun, H. Kazerooni, Adam Zoss. On the Biomimetic Design of the Berkeley lower Extremity Exoskeleton (BLEEX). Proceedings of the 2005 lEEE International Conference on Robotics and Automation, Barcelona, Spain, 2005.

Conflicts of Interest

The authors declare no conflict of interest.

Информация об авторах

Цин Чень, аспирант горного института Кузбасского государственного технического университета имени Т.Ф. Горбачева, старший преподаватель колледжа интеллектуальных производственных систем Чунцинского университета науки и искусств.
e-mail: 1072296534@qq.com
650000, Кузбасский государственный технический университет имени Т.Ф. Горбачева, Россия, г. Кемерово, ул. Весенняя, 28
402171, Чунцинский университет искусств и наук, КНР, г. Чунцин, р-он Юнчуань, пр-кт Хунхэ, 319

Тяньхун Ло, доктор философии (PhD), профессор, директор Чунцинского городского профессионального колледжа.
e-mail: 63077600@qq.com
401331, Чунцинский городской профессиональный колледж, КНР, г. Чунцин, р-он Юнчуань, пр-кт Синлун, 1099

Хорешок Алексей Алексеевич, доктор технических наук, профессор, научный руководитель горного института
e-mail: haa.omit@kuzstu.ru

Варнавский Кирилл Александрович, доктор философии (PhD), заведующий научно-исследовательской лабораторией цифровой трансформации предприятий минерально-сырьевого комплекса
e-mail: varnavskijka@kuzstu.ru

Ермаков Александр Николаевич, кандидат технических наук, доцент, директор горного института
e-mail: ermakovan@kuzstu.ru
650000, Кузбасский государственный технический университет имени Т.Ф. Горбачева, Россия, г. Кемерово, ул. Весенняя, 28

Цзэн Цихан, доктор философии (PhD), старший преподаватель колледжа интеллектуальных производственных систем Чунцинского университета науки и искусств
e-mail: zqh0823@foxmail.com
402171, Чунцинский университет искусств и наук, КНР, г. Чунцин, р-он Юнчуань, пр-кт Хунхэ, 319

DOI: 10.26730/2618-7434-2024-1-43-57

Тао Си, аспирант горного института Кузбасского государственного технического университета имени Т.Ф. Горбачева, старший преподаватель колледжа интеллектуальных производственных систем Чунцинского университета науки и искусств.
e-mail: 419926008@qq.com

Гуанъюн У, аспирант горного института Кузбасского государственного технического университета имени Т.Ф. Горбачева, старший преподаватель колледжа интеллектуальных производственных систем Чунцинского университета науки и искусств
e-mail: 93417197@qq.com
650000, Кузбасский государственный технический университет имени Т.Ф. Горбачева, Россия, г. Кемерово, ул. Весенняя, 28
402171, Чунцинский университет искусств и наук, КНР, г. Чунцин, р-он Юнчуань, пр-кт Хунхэ, 319