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STUDY OF THE OPTIMIZATION PROCESS OF THE EXOSKELETON DESIGN USING GENERATIVE DESIGN METHODS

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Abstract. This study explores the process of design and optimization of exoskeleton for lower extremities using methods of generative design. Due to the unique characteristics and features of the human body, every exoskeleton needs to be adjusted to the working condition of each user, but the development of individual product designs by engineers is highly expensive and takes a lot of time. The study objective is the optimization of the base model of the exoskeleton to working conditions using generative design technology. Optimization is based on human movements and biomechanics, especially on joint torque, which allows to design of construction with acceptable safety factors. Results show highly optimized designs for different materials and a significant reduction in mass and volume relative to the base model. Usage of such technologies saves development time, allowing engineers to focus on more complex aspects of design.

Keywords: exoskeleton, generative design, biomechanics, design, torque, topological optimization.

Introduction

Considering the increasing interest in enhancing human abilities with the help of robotic platforms and exoskeletons, there is a need to use technologies that will allow designing products for the individual characteristics of the user. The interest lies both in increasing the physical strength and endurance of a person when performing loads and in reducing the impact of these same loads on the human body. This will allow the use of exoskeletons of various types to solve such problems as rehabilitation measures after injuries and operations, facilitating movement in diseases of the musculoskeletal system, and support in performing movements and heavy work [1-7].

Significant results have been achieved in this field and many models of exoskeletons for various tasks have been presented, however, these projects have the disadvantage of high manufacturing cost and with the individual characteristics of the user, they can have an even higher cost [1-4, 7, 8].

An exoskeleton is an external device for a part of the body to perform a certain function, which facilitates the performance of tasks by this part of the body. Such devices make it possible to maintain, reduce the load, or even strengthen certain human capabilities. Currently, two main groups of exoskeletons can be distinguished: exoskeletons of passive and active type [4, 6, 8, 9].

The passive type of exoskeletons is used for support during exercises but without the use of active-type elements (electric motors, servo drives). They use mechanical elements (springs, levers) to support, distribute weight, and reduce the load on muscles and joints. This type of exoskeleton is much lighter and easier to manufacture and operate and does not require power sources. They are used to support the body and reduce loads on the musculoskeletal system, using the mechanical properties of materials and mechanisms [7, 10, 11].

Active-type exoskeletons are used not only for support and relief but also to create additional strength for the user. They use electric motors, servo drives, and pneumatic systems in combination with computing and software complexes to control the operation of devices. They are more comfortable and adaptive to the person, and the software allows you to repeat the user's movements with the appropriate accuracy. However, such devices require appropriate power sources and a design that allows the active elements to be attached to the frame [3, 5, 12, 9].

Exoskeletons are used in medicine, as a means of recovery, support, and rehabilitation after injuries in patients, and industry, as injury prevention and reducing the burden on workers when performing heavy and long-term work. Also, exoskeletons are actively trying to be integrated into military affairs, improving the physical qualities of a soldier, taking into account strength, endurance, or the ability to carry an additional load [1-7, 12].

Regardless of the type of exoskeleton, its basic part is the frame, which should be sufficiently ergonomic and user-friendly. The process of designing exoskeletons must include optimization of the resulting structures for the individual characteristics of the person who will use this device. For this purpose, anthropometric data of the user's body, anatomy of the human body, and biomechanics of movements are taken into account and included in development. Otherwise, non-compliance with the parameters will cause inconvenience to the user, which may lead to injury [12, 13].

Construction creation and optimization technologies using generative design methods can be applied for simplification of the design process. Generative design uses main parameters, that relate to the design of the product, but their correct definition and understanding of product working conditions and the studied parameters should be evaluated at the beginning. However, the correct study of the interaction of the exoskeleton structure with the user, its compliance with the loads and conditions of use, and the location and movement of the structural elements rest on the engineer [14-16].

Generative design allows you to design objects that are optimized even before the stage of submission to production. Thanks to this technology, construction development includes work conditions, material properties, loads, and topological optimization at the starting stage of the project. When creating a prototype, the technology allows you to reduce the volume or weight of the product without losing its properties. If changes are necessary, the engineer defines new constraints and generates a new prototype, that meets the new conditions [14-17].

Generative design can use base models for generation or build models from scratch. The technology makes it possible to generate a finished product under given restrictions, while generative design creates several variants of the product under specified conditions for one model. The generation process takes into account the materials and the process of manufacturing the product with the appropriate equipment, such as 3D printing with plastic filament from different materials [14-17].

In this study, the optimization process of the basic 3D model of the exoskeleton for the lower limbs was considered. For this, the basic model, its creation, and compliance with the basic human parameters were investigated. The model is a continuous frame with predetermined places for fixing the main joints and elements on this frame. The proposed product has 6 degrees of freedom for the leg, which includes mechanisms corresponding to the joints of the leg. This work explores the potential of using generative design technologies to optimize mass from a solid initial design under loads resulting from standard exercises and various materials used in 3D printing.

Problem Statement

Evaluation of the biomechanics of the lower limbs is an important part of gathering information for the design of ergonomic exoskeletons for this part of the body. For this, it was necessary to determine the anatomical and biomechanical features of the limbs themselves, which include the anthropometric parameters of the leg, the properties and mechanics of the joints and muscles, the possibility of attaching the frame to the limb, and workloads that will affect the.

Anthropometric indicators are divided into 2 groups: general indicators and indicators for the lower extremities. General indicators include a person's height, weight, and mass index, from which indicators for the lower extremities can be determined individually. Indicators for the lower limbs are: leg length;

thigh, leg, foot length; hip and lower leg girths; knee, ankle, heel height; foot width and toe length; hip, knee, and ankle angles. These data were used to determine the dimensions of the basic 3D model of the exoskeleton [3, 18-22].

The properties and mechanics of the joints and muscles are necessary to define the freedom of movement of the basic 3D model of the exoskeleton. The lower limb consists of 3 joints (femoral (hip), knee, ankle), which form 6 degrees of freedom of movement. The hip joint is a ball-and-socket joint that is actuated by the thigh muscles, allowing movement in 3 planes. The knee and ankle joints are simple hinge joints that, in conjunction with the appropriate muscle groups, allow movement in 1 plane of motion and little movement in others. Thus, the basic model of the exoskeleton should have appropriate mechanical joints [18-24]. Examples of joints are presented in Fig. 1.

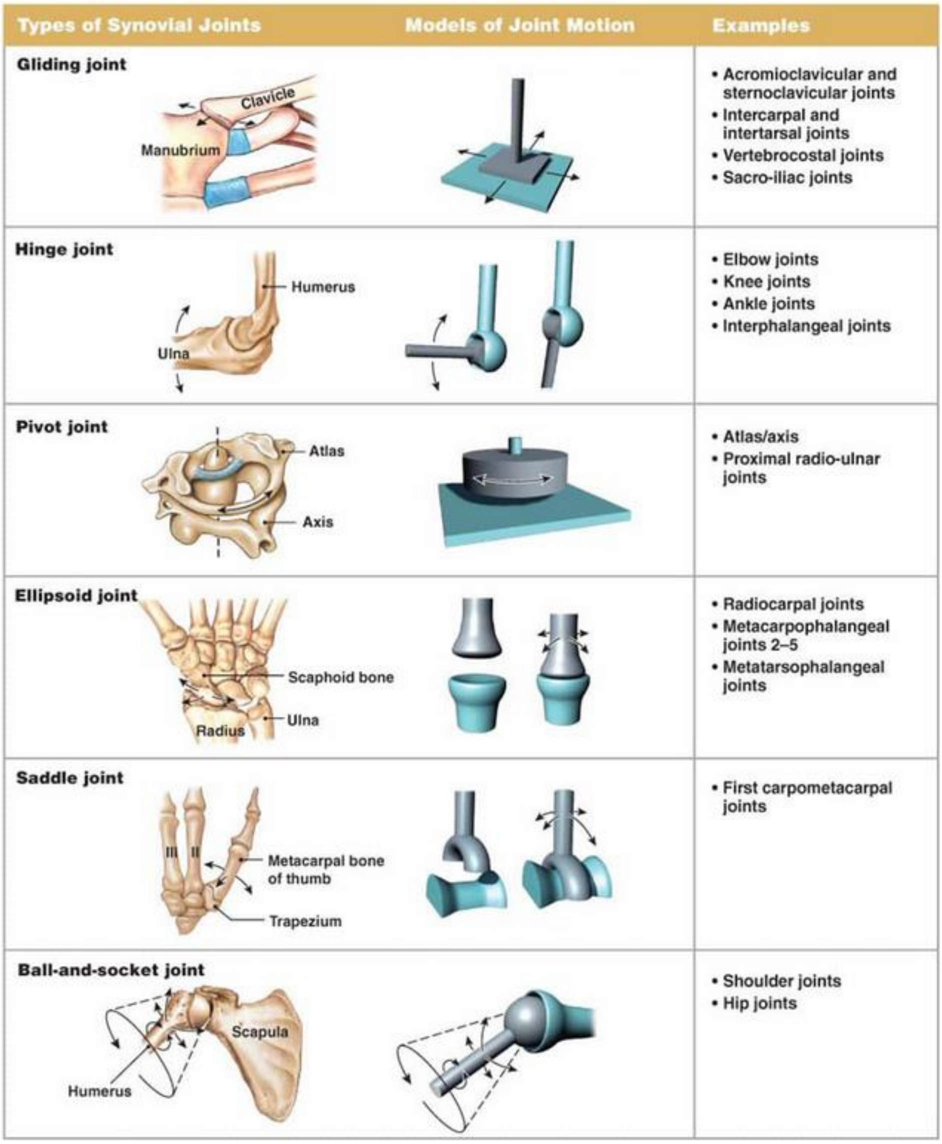


Fig. 1. Types of joints and their mechanical models. Source: https://nurseslabs.com/skeletal-system/

Attachments are individual devices for creating interaction between the structure and the limb. Their position is regulated by the possibility of attaching to the frame and, accordingly, transferring the load to this frame. Because of this, the base model must have reserved positions for mounting those attachments.

Working loads are specified loads during standard movements and exercises. Standard exercises include walking, running, climbing/descending stairs, squats, etc. They are measured as a percentage of body weight. From these data, the loads at the corresponding moments of movement are determined, which will allow to collection of the necessary restrictions [19, 21, 22, 23-26]. The percentage ratio of load to body weight for the respective joints is presented in Table 1.

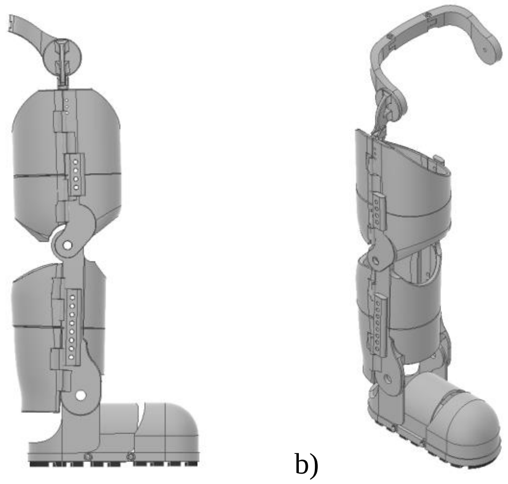
Table 1.

Characteristics of loads during exercises relative to body weight (BW)

Exercise	Hip joint, % BW	Knee joint, % BW	Ankle joint, % BW
Walk	100-250	150-250	120
Run	200-300	200-300	275
Rise from a sitting position	30-50	200-300	200-300
Stairs ascending	200-300	200-300	200-300
Stairs descending	150-250	250-350	150-200

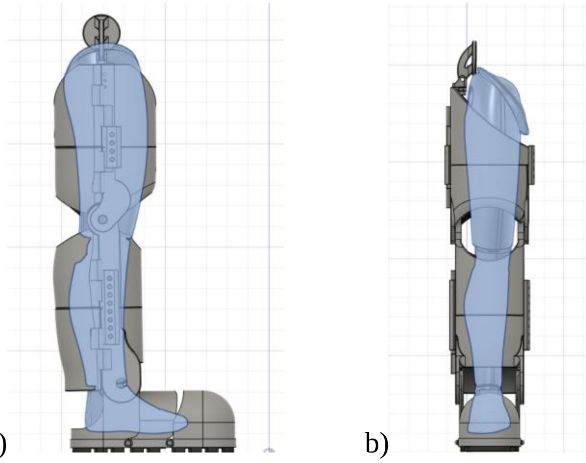
According to the data determined in the previous subsection, a 3D model of the exoskeleton is formed, as well as taking into account the method of manufacturing the product using 3D printing. This means that each part is designed to be printed on the corresponding printer, namely for printers with a printing area of 200x200x250 mm.

The model is solid elements that cover the leg according to anthropometric indicators. The elements are organized into larger assemblies according to the parts of the leg and form the corresponding joints. All elements are connected. The former model is shown in Fig. 2-3.



a) b)

Fig. 2. Basic solid 3D exoskeleton model.
a) – side view, b) – isometric view.



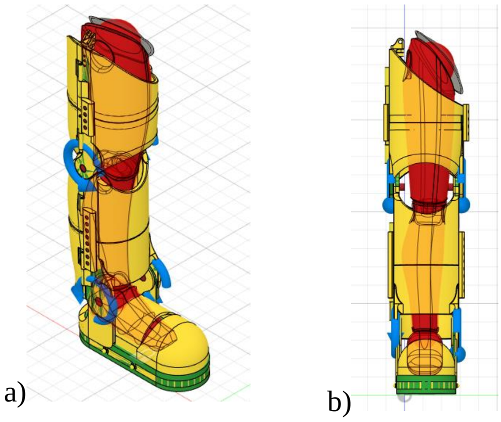
a) b)

Fig.3. The basic solid 3D model of the exoskeleton with the position of the leg in the exoskeleton:
a) – side view, b) – front view.

The basic 3D model is designed in the educational version of Autodesk Inventor 2023 by the defined parameters and dependencies between elements. The model consists of 4 parts: a pelvic attachment with a hip joint, a thigh structure, a lower leg structure, and a foot structure.

Optimizing the mass of the exoskeleton structure of the lower limbs is critical to ensure the efficiency and comfort of using these devices. Reducing the weight without losing the rigidity and stability of the structure allows to reduce the burden on the user, which is especially important for people who need assistance in movement, such as trauma patients or the elderly. Analysis of the torque that occurs during movement allows you to identify optimal solutions for the location of components that affect the balance and maneuverability of the exoskeleton. This, in turn, leads to the creation of lighter, but strong structures that provide the necessary support.

In addition, the use of modern materials and modeling technologies allows to achieve an optimal ratio between strength and weight. Topological optimization and computer simulation of motion mechanics, which uses generative design, provide the possibility of detailed analysis of loads and structural elements. This helps reduce material redundancy, which in turn increases the efficiency of the exoskeleton.



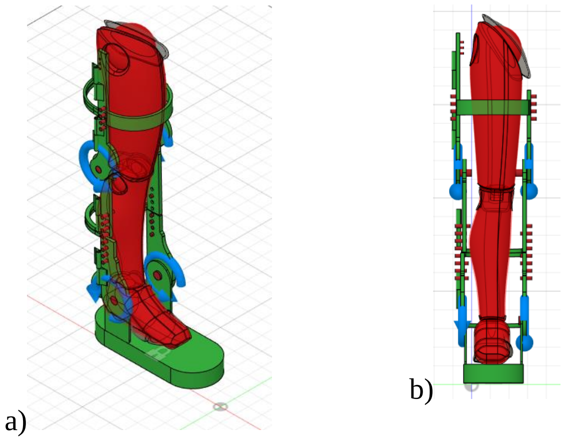


Fig. 4. 3D model of the exoskeleton in the environment: a) – side view, b) – front view.

Fig. 5. 3D exoskeleton model in an environment without a starting form: a) – side view, b) – front view.

To carry out design optimization, it is necessary to determine the initial conditions, materials, and limitations for the specified model. This includes determining the initial shape, determining the parts to be preserved, determining the inaccessible areas, determining the initial conditions, determining the load, determining the materials, and determining the manufacturing method. Preparation for the experiment is shown in Fig. 4-5. The starting shape is marked in yellow, forbidden zones in red, protected zones in green, and blue arrows - directions of torques.

Results and Discussion

The basic model was designed in the Autodesk Inventor 2023 CAD environment. PET plastic from the Autodesk material library served as the main material for the basic model. A complete model with a mass of 23.25 kilograms and a volume of 14913430 mm^3 was obtained, which is shown in Fig. 6. The resulting model was optimized using a generative design. Generative design simulations were performed in the Autodesk Fusion 360 environment, which allowed the integration of both programs to simplify the simulation of the experiment.

Since the Autodesk Fusion 360 environment does not support generation for assemblies, the model was cast to the body of a solid structure. The experiment consisted of 5 simulations, one for each material. The table of results is presented in Table 2. The same conditions and loads are assigned to each simulation. 5 optimization results were obtained from the selected materials. An example of simulation results is shown in Fig. 7, and an example of simulation characteristics is shown in Fig 8.

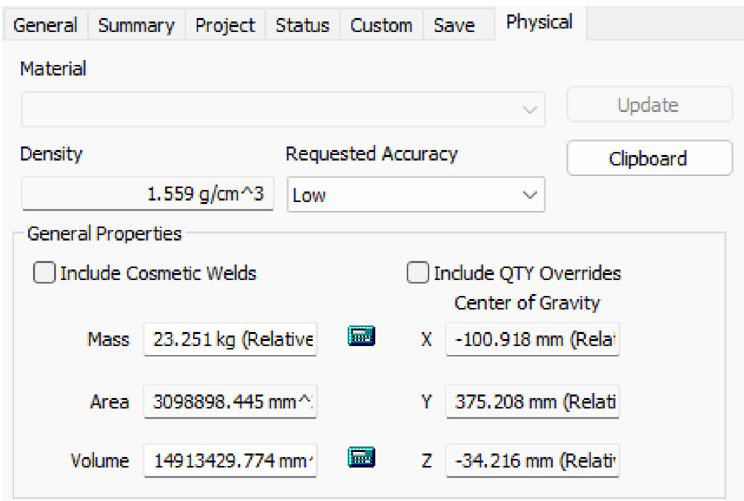


Fig. 6. Physical characteristics of the base model.

Fig. 7. The resulting 3D model of the exoskeleton after optimization.

Fig. 8. Characteristics of the obtained 3D exoskeleton model after optimization.

Table 2

Construction generation results

Experiment №	Material	Volume, e^{+6} mm^3	Mass, кг	Suitability, %
1	ABS	4,513	4,783	66,194
2	PAEK	4,549	6,004	35,82
3	Нейлон	4,524	5,067	85,491
4	PC/ABS	4,524	4,976	87,178
5	PET	4,579	7,056	45,947

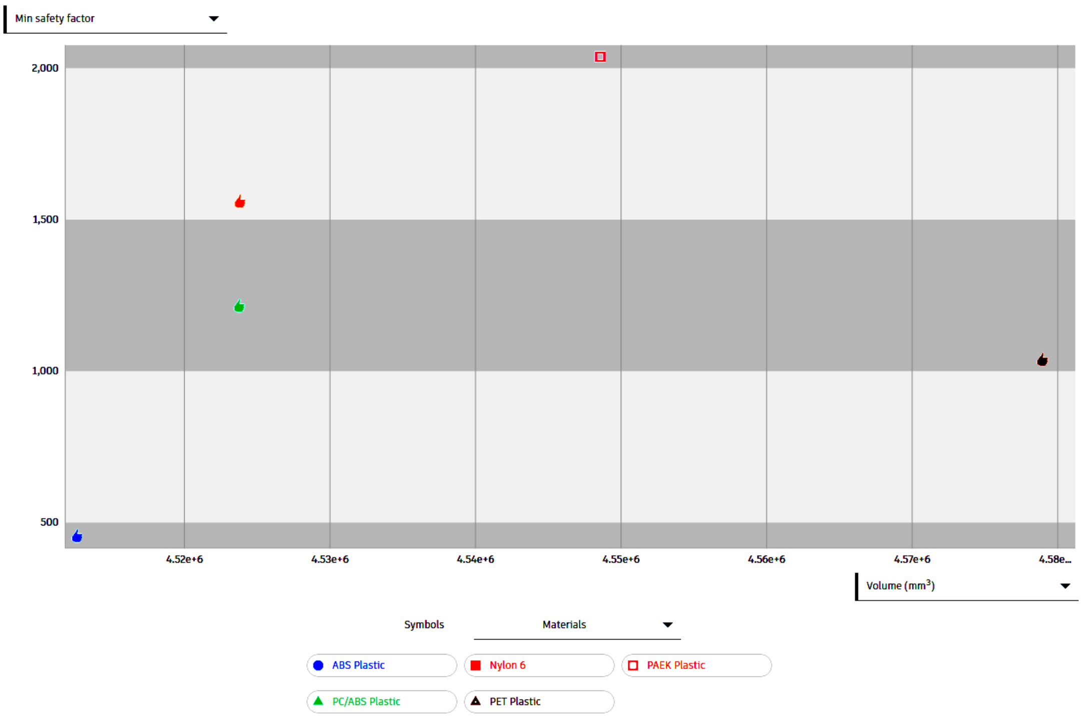


Figure 9. Structure efficiency relative to the volume of the structure.

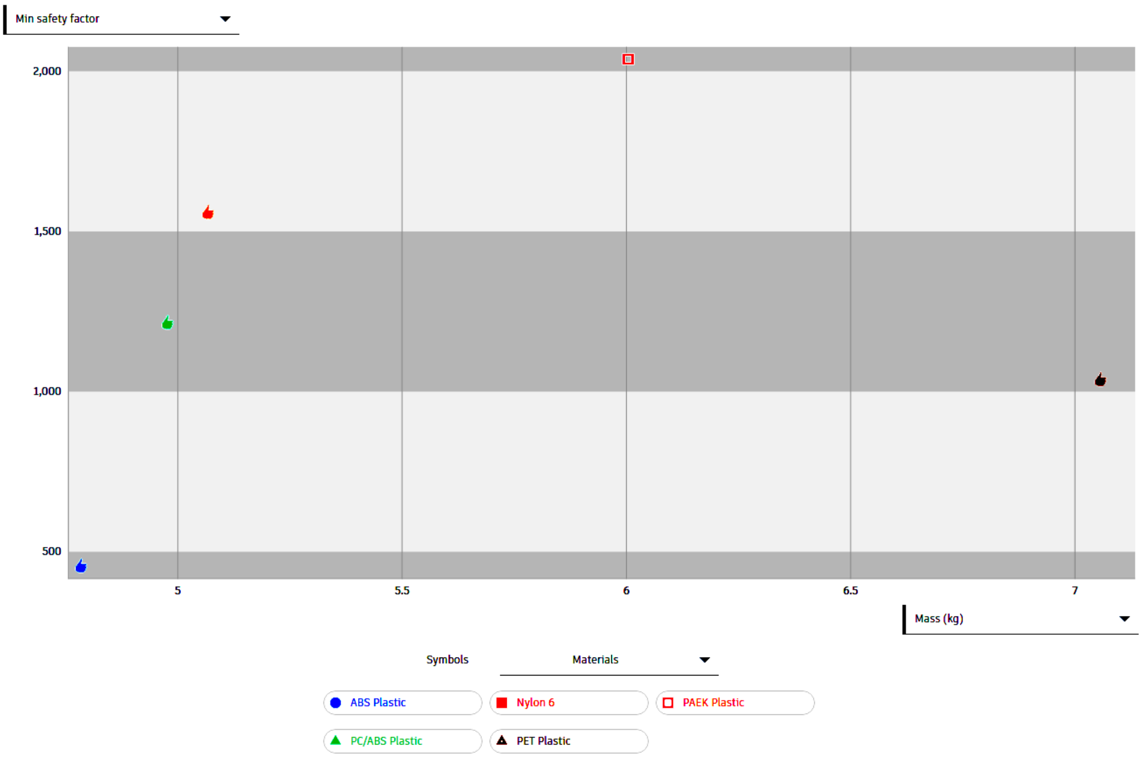


Figure 10. Structure efficiency relative to mass of the structure.

As a result, a set of optimized structures was obtained, which will allow the engineer to choose a suitable structure that fully meets the requirements of its use. The set is characterized by 5 materials and manufacturing technology using 3D printing. Industrial plastics are used as a selection of materials, namely: ABS, PC/ABS, PAEK, PET, and nylon.

The study showed a decrease in the mass of the structure from 3 (PET plastic) to 5 (PC/ABS plastic) times, and the volume by 3 times, relative to the initial characteristics. The results are given in the relative efficiency of the obtained models in Figures 9-10 and determined by mass and volume.

Conclusions

Exoskeletons are innovative technologies that significantly improve the mobility and physical support of users, especially in the medical and industrial fields. They provide support for the lower limbs, reducing the load on joints and muscles, which is important for rehabilitation and increasing work productivity.

Generative design, due to its ability to automatically generate optimized shapes based on given parameters and constraints, is becoming a powerful tool in designing exoskeletons. It allows for the creation of light and strong structures that take into account the mechanics of movement and loading, which increases the overall efficiency and functionality of devices. Using generative design promotes innovation by reducing development time and allowing engineers to focus on more complex aspects of design.

During the study, computer modeling of the basic model of the exoskeleton was carried out. Anthropometric, anatomical, and biomechanical features of the lower extremity were collected and included in the design. The optimization of the base model was carried out under the specified conditions and limitations using generative design, which showed a significant reduction in the mass and volume of the final model compared to the base model.

The obtained results show a significant reduction in mass relative to the base model by 3-5 times (depending on the material) and a reduction in volume by 3 times. It also allows you to identify the weak points of the design and correct inaccuracies even in the basic model.

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ДОСЛІДЖЕННЯ ПРОЦЕСУ ОПТИМІЗАЦІЇ ДИЗАЙНУ ЕКЗОСКЕЛЕТУ ЗА ДОПОМОГОЮ МЕТОДІВ ГЕНЕРАТИВНОГО ДИЗАЙНУ

Отримано: Листопад 04, 2024 / Переглянуто: Листопад 15, 2024 / Прийнято: Листопад 20, 2024

Анотація. В статті досліджується процес проектування та оптимізації екзоскелету нижніх кінцівок за допомогою методів генеративного дизайну. Через унікальні характеристики та особливості людського тіла кожен екзоскелет потрібно налаштовувати під умови роботи кожного користувача, але розробка інженерами індивідуального дизайну продукту коштує дуже дорого та займає багато часу. Метою дослідження є оптимізація базової моделі екзоскелета до умов роботи за допомогою технології генеративного проектування. Оптимізація базується на рухах людини та біомеханіці, особливо на суглобовому моменті, що дозволяє проектувати конструкцію з прийнятними коефіцієнтами безпеки. Результати демонструють високооптимізовану конструкцію для різних матеріалів і значне зменшення маси й об'єму порівняно з базовою моделлю. Використання таких технологій економить час розробки, дозволяючи інженерам зосередитися на більш складних аспектах проектування.

Ключові слова: екзоскелет, генеративний дизайн, біомеханіка, проектування, крутний момент, топологічна оптимізація.