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*Original Article*

# Optimal Synthesis and Development of a Lower Limb Exoskeleton Control System with Gravity-Independent Suspension

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***Abstract*** - *The relevance of the study is due to the need to develop innovative technologies that can increase the mobility and efficiency of people in different gravitational environments, which has the potential to have a substantial impact on the fields of medicine, industry, and space activities. This study aims to analyse the control system of the exoskeleton for the lower limb with a gravity-independent suspension to identify possible improvements and optimisations in its functionality and efficiency. Among the methods used are the analytical, classification, functional, statistical, and synthesis methods. The control system of the exoskeleton for the lower limb with a gravity-independent suspension was thoroughly analysed. The mechanical design had to be optimised for ergonomics and weight, and the electronics included advanced sensors and microcontrollers for precise control. The software should include algorithms for stabilisation and adaptation to the environment. Energy management should be designed to extend battery life. The exoskeleton must comply with safety and ergonomics standards. The possibilities of scaling production and user training are considered, which makes this system promising for medical and industrial fields and emphasises its potential in training and integration into everyday life. The analysis of the innovative control system of an exoskeleton with a gravity-independent suspension in this study has prospects for use in medicine, increasing efficiency in industry and maintaining mobility in various gravity conditions, opening up new horizons in the field of technological solutions to improve the quality of life.*

***Keywords*** - *Mechanical design, Safety standards, Adjustable mechanism, Analysis, Energy management.*

## 1. Introduction

The study of lower limb exoskeletons with suspension that does not depend on gravity has become an important area of research for finding new ways to improve mobility and efficiency in various gravitational environments. Despite notable advancements in exoskeleton technology, numerous extant designs exhibit constraints in terms of adaptability, efficiency, and conformity with safety and ergonomics standards, particularly in the context of diverse gravitational conditions. This research project addresses these challenges by focusing on a gravity-independent suspension system, which offers a novel approach to achieving user comfort and efficiency. A significant shortcoming of current research is the lack of incorporation of adaptable control mechanisms that can respond dynamically to the specific movements of the user and changes in the surrounding environment. For instance, while D. Bizhanov et al. [1] have investigated the advantages of gravity-independent exoskeletons for enhancing mobility under diverse circumstances, their work lacks the integration of biometric data that could facilitate precision and personalisation. Similarly, R. Liseichikov and I.N. Shcherbak [2] emphasised the importance of ergonomic design. However, they did not investigate the use of modern lightweight materials or adaptive algorithms, which are essential for user-centred applications.Control systems are of critical importance with regard to the functionality of exoskeletons [3]. Advanced sensors and microcontrollers, capable of adapting to various environmental changes and user needs, can facilitate precise control, as noted by O. Zubkov and V. Torchynskyi [4]. The advent of sophisticated sensor technologies, including high-sensitivity accelerometers and gyroscopes, has enhanced precision in tracking movements and dynamic interaction with the user, as observed by G. Balbayev et al. [5].The issue of energy efficiency remains a key area of focus, given the need for exoskeletons to operate for extended periods without frequent recharging. As N.

Zhetenbayev et al. [6] observe, exoskeleton energy management is witnessing regenerative systems integrating kinetic energy into electrical energy. This development can potentially prolong operational time and diminish the necessity for bulky batteries. Such enhancements are crucial for applications in industry, where workers may necessitate continuous assistance throughout extended work periods. Moreover, incorporating Artificial Intelligence (AI) in exoskeleton systems has facilitated the advent of adaptive and personalised control mechanisms. Incorporating AI algorithms enables the exoskeleton to learn and anticipate user movements, thereby enhancing safety and responsiveness in real-time [7].

As observed by R. Bondarenko and G.K. Kalakova [8], AI also enables remote control and monitoring capabilities, which can be advantageous in medical applications where specialists require the ability to monitor patient progress remotely. The purpose of the study is to optimally design the Actuating Mechanism (AM) of the lower limb exoskeleton of a combined type, which has the advantages of both active and passive exoskeletons based on the advantages of closed kinematic circuits (increased rigidity, load capacity, specific power) and gravitationally independent suspension (minimum number of active power drives, simplicity of design, and unloading of the control system).

## 2. Materials and Methods

The analytical method helped in a detailed study of the exoskeleton's functionality, identifying its strengths and weaknesses and areas requiring improvements. This method provided a deep understanding of the control processes and the system's interaction with the user, which substantially enriched the understanding of the topic under study and contributed to forming the foundations for further innovations in the development of exoskeletons. Using the formalisation method, the structure and interaction of the components of the control system of the lower limb exoskeleton with a gravity-independent suspension were examined in detail, which allowed potential improvements in mechanical and electronic design and optimised control algorithms to be identified.

Applying the axiomatic method in examining the exoskeleton control system included formulating key functioning principles, including stabilisation of movements, ensuring user safety, effective environmental interaction, and other important aspects. These axioms served as the basis for further study and optimisation of the system, ensuring its effective functioning in various gravity conditions. The deduction method helped in the logical conclusion of cause-and-effect relationships in the functioning of the exoskeleton control system. Focusing on this method helped to identify the basic principles and patterns underlying the effective interaction of system components. Using the synthesis method, various components of the exoskeleton control system were combined into a single and optimised structure. This method created a balanced system that includes mechanical, electronic, and software components interacting with high consistency. The synthesis process contributed to creating an effective control system that considers the characteristics and requirements of each component and, as a result, provides higher performance and precision control of the exoskeleton. The classification method helped to systematise various aspects of the exoskeleton control system, identify the main categories, and determine the characteristics of each of them. This method provided an approach to organising information, allowing for a better understanding of the structure and interrelationships of the system elements.

In the course of the study, the abstraction method was used to identify general concepts and abstract models reflecting the essence of the functioning of the control system of an exoskeleton with a gravity-independent suspension. This method allowed for simplifying the complex details of the system, focusing on key aspects such as stabilisation mechanisms, effective interaction with the environment and ensuring user safety. This method allowed the consideration of exoskeletons to be more abstract, which is useful for generalising the results. Using the induction method, general patterns and principles were derived based on specific observations and data obtained during the study of the exoskeleton control system.

This method allowed identifying key trends, abstracting from specific cases, and formulating general principles underlying the effective functioning of the exoskeleton. With the help of generalisation, the patterns and features of the exoskeleton control system were identified. The results allowed for determining key parameters and functional characteristics that affect the system's efficiency in conditions of gravitational independence. This method also contributed to developing general principles for designing and managing exoskeletons, considering their application in various fields such as medicine, industry, and space activities.

### *2.1. Advanced Materials and Manufacturing Techniques*

To further optimise the mechanical design of the lower limb exoskeleton, the selection of modern materials and advanced manufacturing technologies is of paramount importance. This is done to reduce weight while maintaining structural integrity and functionality. It is recommended that the following considerations be explored: Reducing overall weight while maintaining the system's strength and durability is a primary challenge in exoskeleton design. The utilisation of advanced composite materials, such as carbon fibre-reinforced polymers, is becoming increasingly prevalent in the construction of exoskeletons. These materials offer a high strength-to-weight ratio, providing the requisite rigidity and durability without significantly adding weight. Furthermore, joint components employ thermoplastic composites, combining strength and flexibility to enable adaptive motion while maintaining the necessary mechanical properties [9].

Additionally, metals such as titanium alloys are considered structural components due to their high strength, lightweight, and fatigue resistance, making them ideal for high-load bearing applications. Incorporating lightweight metals in non-structural components, such as frame support structures and joints, ensures optimal performance while reducing the overall mass of the system. Additive manufacturing, or 3D printing, is a pivotal technology in producing exoskeletons, as it creates highly personalised components [10, 11]. This technology allows for the creation intricate geometries, such as lattice structures, that offer strength while utilising minimal materials. Furthermore, 3D printing facilitates rapid prototyping and testing, guaranteeing that exoskeleton designs are readily adaptable to varying user requirements and environments.

The capacity to produce components on demand and adapt them to the specific anatomical and functional requirements of users has the potential to result in more efficient and personalised devices.Incorporating intelligent materials, such as Shape-Memory Alloys (SMAs), can markedly enhance the adaptability of the exoskeleton. These materials can change shape in response to external stimuli, such as temperature or electrical input. This enables the exoskeleton to undergo a corresponding change in its structure on a dynamic basis, in accordance with the movements of the user and the characteristics of the external environment.

SMAs are particularly useful in joints and other dynamic components, enabling the exoskeleton to adapt to various activities, from walking flat surfaces to navigating uneven terrain.Furthermore, the integration of soft robotics materials, which emulate the properties of biological muscles, can enhance the flexibility and comfort of the exoskeleton. Such materials can provide smooth, responsive movements, enabling the device to function according to the user's natural biological mechanisms. Adopting sustainable manufacturing practices will be critical as exoskeletons move toward large-scale production. We use injection moulding and precision casting techniques to create lightweight, high-performance components. Furthermore, the implementation of automated assembly lines will not only reduce manufacturing costs but also ensure consistent quality across units. Moreover, sustainable sourcing of materials and energy-efficient production processes will contribute to minimising the ecological footprint of the exoskeletons, aligning with global trends toward environmentally conscious manufacturing.

## 3. Results

Exoskeletons are an innovative technology that promises to transform the fields of medicine, industry and other areas of human activity. Defining clear goals and objectives in using exoskeletons is becoming a key stage in the research of this technology. The initial goal of using exoskeletons is to improve the mobility and efficiency of people in different gravitational environments.

**Fig. 1 A model of the musculoskeletal mechanism of the exoskeleton for the lower limb**

*Source: [12].*

For example, the main goal in medical applications may be to restore mobility in people with musculoskeletal disorders (Figure 1). In heavy industries, exoskeletons can be aimed at reducing fatigue and increasing workerproductivity. The problem is constructing an Executive Mechanism (EM) based on open kinematic circuits and the desire to blindly copy the biological principles of the organisation of limb movement. Almost the entire cycle of engine operation consists of unsteady modes of intensive acceleration and braking. It is for this work that the main engine power is spent.

The main idea is to develop a combined type of lower limb exoskeleton, which has the advantages of active and passive exoskeletons due to a gravity-independent topology, which allows reducing power drives and simplifying the design, substantially unloading the control system. It is necessary to solve a set of problems of structural and parametric optimisation of EM, based on closed kinematic circuits, to do that, which allows increasing rigidity, load capacity, and specific power compared with existing "anthropomorphic" structures. It is required to develop methods of analysis and synthesis, mathematical modelling, multicriteria optimisation, numerical calculation and optimal design programmes, anatomical parameterisation methods, a control system, and an experimental study of the proposed biomechanical system model.

The mechanism of an exoskeleton designed for rehabilitation therapy of the lower extremities should mimic the movements characteristic of human lower extremities [13]. The inability to directly measure normal gait in patients due to impaired motor functions underlines the importance of rehabilitation training and assessment of normal gait parameters, which is critical in clinical practice. People with disabilities often follow certain trajectories in the rehabilitation process. These predetermined trajectories can be identified by analysing data on normal gait. Examining the characteristics of a person's gait using the analysis of step pits allows for determining these trajectories. The length, width, and speed of the step are key parameters for determining the characteristics of a person's gait. Consequently, the kinematic parameters and structural features of the human body substantially impact the characteristics of human gait.Walking speed affects a person's gait, as seen by analysing gait parameters and angles formed by joints [14, 15]. This is confirmed by gait data recorded and analysed at various speeds on walking simulators and treadmills [16]. Since most rehabilitation robots use body support systems during training, analysing a person's treadmill gait is necessary. Scientific studies have also shown that height as a structural parameter is limited compared to the effect of walking speed.

This was established by comparing the correlation differences between regression models using velocity and normalised velocity (divided by leg length) [17] and applying stepwise regression methods to models that include height as a parameter. The exoskeleton control system for the lower limb should effectively solve several key tasks aimed at optimising mobility and improving the user's performance in various gravitational conditions [18]. The exoskeleton should provide mobility support, including walking, running and other motor activities, even in conditions of gravity other than Earth's. An important task is to reduce fatigue and stress on the muscles and joints of the user, which requires effective load distribution [19, 20]. The system should also provide improved ergonomics, granting intuitive operation and comfortable use.

Safety and compliance with occupational health and safety standards are also part of the tasks of the system. Finally, adaptation to various use scenarios – from medical institutions to industrial enterprises and space stations – is an integral part of the functionality of the exoskeleton. These tasks form the basis for developing innovative management systems to transform the understanding of human mobility and performance in various environmental conditions. The optimised control system of the lower limb exoskeleton with gravity-independent suspension is an integrated approach combining advanced mechanical solutions, electronics, software and energy-saving technologies [21]. These proposals should be described in more detail.

The exoskeleton should have the following novelty: increased rigidity, load capacity, and specific power of the executive layout by taking advantage of closed kinematic circuits; minimised number of active power drives, simplified design, and a substantially unloaded control system by decomposing motion according to degrees of freedom and using a gravitationally independent suspension. In the study by O. Kyzymchuk and L. Melnyk [22], diagrams of reconfigurable four-link mechanisms describing horizontal lines are provided. The diagram shows various kinematic schemes of reconfigurable 4-link mechanisms describing a family of horizontal lines. This design includes two actuators (electric drive).

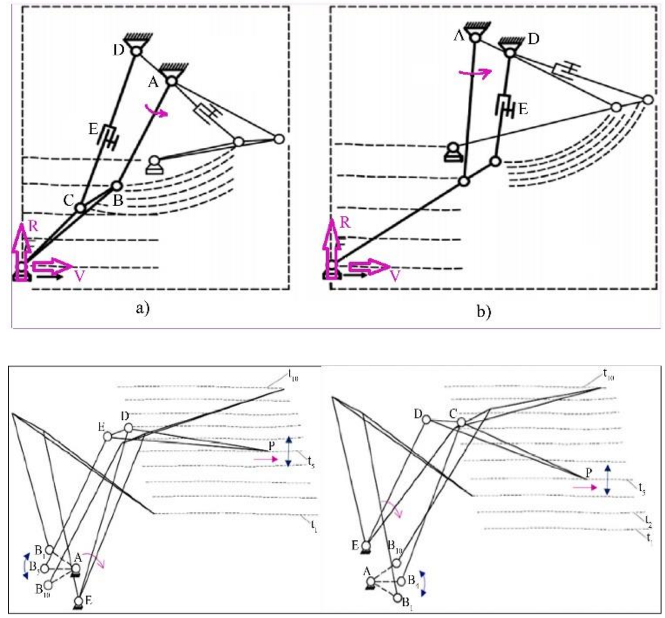


**Fig. 2 Schemes of reconfigurable four-link mechanisms**

Note: ABCDE – hinges; R – leg reaction; P – connecting rod point; $t_1$, $t_2$, $t_4$, $t_5$, $t_{10}$ – trajectory lines (position movement); V – leg speed.
*Source: Compiled by the authors.*

When the angular position of the AB link is changed, the connecting rod point P of the BCDE four-link approximates various horizontal lines. Consequently, the velocity vectors V and G of the links are orthogonal, and the power spent on horizontal movements of the load G is 0. Actuators (electric drives): in the hinge E – low-power; in the hinge A – medium-power (Figure 2). Thus, only the AB link changes the vertical Cartesian coordinate of the working point P, whereas the influence of the second input link ED on this coordinate is negligible. As a result, the drive in hinge E is "gravitationally independent" (mechanical energy for lifting and lowering the load is spent only by the drive in hinge A), substantially reducing the energy consumption of the specified drive. The same idea can be used to construct lower limbs with gravity-independent suspension.

The adjustable leg levers that can be used for the exoskeleton of the lower extremities are shown here. The solution uses only one drive motor, and the principle of gravitational independence can be implemented if the base of the link goes in a straight line relative to the body in the support phase. This design has a gearbox that transmits motion through the shaft to the electric motor elements of two mechanisms for the left and right legs. As a result, management is greatly simplified, and energy consumption is reduced. The advantage of the design presented by the authors will be the use of adjustable mechanisms to adapt to terrain irregularities. The most straightforward block diagram of an adjustable mechanism for multipath generation can be obtained from a four-link ACDE generator by adding input connection B (Figure 3).

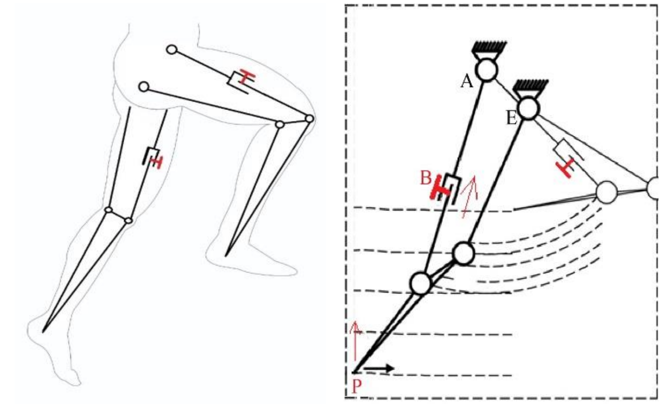


**Fig. 3 Synthesis of a four-link with adjustable crank length for multipath generation**

*Source: Compiled by the authors.*

The lower limb's exoskeleton utilises a comprehensive array of advanced sensors and microcontrollers, ensuring high precision and efficient operation. The system incorporates inertial measurement units, comprising highly sensitive accelerometers and gyroscopes, for the real-time tracking of the user's movements. The sensors provide data on acceleration and angular velocity, enabling the exoskeleton to dynamically adjust and maintain balance in response to the user's actions. To illustrate, the accelerometers quantify linear acceleration across diverse axes, thus endowing the exoskeleton with comprehensive spatial awareness. Meanwhile, the gyroscopes monitor rotational movements, facilitating the precise realignment of the limbs with minimal latency. Furthermore, the system employs ARM Cortex-M series microcontrollers, chosen for their high processing power and low energy consumption. The microcontrollers are responsible for the management of sensor data, the execution of control algorithms, and the communication with actuators, thereby ensuring the seamless operation of the exoskeleton.

The control system uses PID (Proportional-Integral Derivative) algorithms, which let the exoskeleton's mechanical movements be constantly changed based on real-time sensor inputs. This ensures that the user can interact with the system smoothly and responsively. Furthermore, the system incorporates pressure and load sensors into the exoskeleton's footplates. These sensors monitor the pressure distribution on the user's feet, providing feedback that facilitates load redistribution and enables adaptation of the walking dynamics to varying surfaces. This complex network of sensors and microcontrollers is fundamental to the exoskeleton's ability to adapt and respond effectively in various environments, from medical rehabilitation settings to industrial applications. The artificial intelligence embedded in the exoskeleton software is a highly efficient system that combines the analysis of user movement patterns and dynamic optimisation of the exoskeleton functionality [23]. This integration will create an intelligent control system capable of adapting to different conditions and user needs. Artificial intelligence algorithms embedded in the software have the adaptive ability to predict changes in gravity conditions and dynamically respond to them [24]. This means that the exoskeleton will automatically adapt to changes in the user's environment or movement style, providing optimal support and comfort. The software component with artificial intelligence will not only respond to current conditions but will also be able to anticipate possible changes, warning the system against delays or ineffective reactions. This important property will contribute to a smoother and more natural interaction between the user and the exoskeleton, ensuring optimal system operation in various use scenarios. Energy-saving technology in the concept of the exoskeleton of the lower extremities is a set of approaches aimed at effective management and use of energy [25-27]. The energy recovery system will become one of the key elements, including a mechanism capable of converting kinetic energy obtained from movement into electrical energy, which is then used to charge batteries.

In addition to the regeneration system, using energy-efficient components in the form of 2 electric motors in the mechanical and electronic design of the exoskeleton will contribute to reducing overall energy consumption. This involves using components with a high degree of efficiency, reducing energy losses during transmission, and using materials with a low coefficient of friction. Optimised control algorithms also play an important role in minimising the energy consumption of the exoskeleton. These algorithms should be designed in such a way as to rationally distribute and control energy in accordance with the user's movements and the current operating conditions of the exoskeleton [28]. Their goal is to ensure efficient and accurate system operation with minimal energy consumption, which contributes to the device's long–term autonomous operation and increases its efficiency. Remote control and monitoring within the framework of the exoskeleton for the lower extremities will provide the user with high flexibility and ease of operation of the device.

This can be achieved using a mobile application that allows the user to control the exoskeleton and monitor its operation from anywhere at a distance. The mobile application will be able to configure operation parameters, monitor the device status, and remotely interact with the exoskeleton functions [29]. Virtual Reality (VR) interfaces are another innovative element that facilitates user control and interaction with the exoskeleton [30, 31]. VR systems will create a virtual space where the user can visualise and control the operation of the exoskeleton. This will add abstraction and facilitate the perception of the device's operation, making interaction more natural and intuitive [32]. Such technological solutions will not only improve the usability of the exoskeleton but also expand the possibilities of its application in various fields such as medicine, industry, or virtual reality. These optimised characteristics substantially increase the efficiency and comfort of using a lower limb exoskeleton with gravity-independent suspension. Exoskeletons and gravity-independent suspensions represent advanced technologies that can transform medicine, industry, and mobility [33, 34]. Examining existing technologies in this area becomes an integral stage for identifying ways to improve and develop innovative solutions. Developing electronics and using advanced sensors are becoming cornerstones in creating innovative exoskeletons, providing precise motion control and environmental monitoring [35]. Electronics is becoming a mosaic connecting mechanics and information technology to achieve optimal performance. Integrating microcontrollers into the exoskeleton control system provides centralised control and the possibility of software configuration in real-time [36]. This allows the operation of the exoskeleton to be adapted to the changing needs of the user and the environment.

### *3.1. Biometric Data Integration in Exoskeleton Control*

Incorporating biometric sensors into the control system of the exoskeleton can greatly enhance the device's personalisation and responsiveness to the user's physiological conditions. Integrating biometric data, including heart rate, muscle activation (via electromyography), and skin temperature, could facilitate real-time adjustments that enhance the user's comfort and safety. To illustrate, data obtained from muscle sensors may enable the system to detect indications of user fatigue, thereby facilitating the automatic reduction of the mechanical load during rehabilitation sessions. Similarly, monitoring heart rate variability can assist in adapting the device's assistance level in accordance with the user's physical state, thereby reducing the risk of overexertion.

This approach is consistent with the growing trend toward intelligent assistive devices that are not only capable of performing predefined tasks but also adapt dynamically to the individual's needs. Incorporating biometric feedback in the exoskeleton could facilitate a more natural interaction, enabling the control system to optimise movements and reduce unnecessary strain on muscles and joints. Implementing such a system would necessitate integrating advanced sensor fusion techniques and algorithms capable of interpreting biometric data in real time. This would ensure the robustness and adaptability of the device in diverse usage scenarios, including medical rehabilitation, industrial support, and personal mobility in low-gravity environments.

Sensors, including accelerometers and gyroscopes, collect human movement data. Accelerometers measure acceleration, and gyroscopes – angular velocities, allowing the system to track each body part's position and movements accurately. These data are the basis for the correction and adaptation of the exoskeleton. In addition to the main sensors, using additional sensors complements the functionality of the exoskeleton. Such sensors may include pressure, temperature, and even biometric sensors to monitor the user's physiological parameters. This provides additional data for the control system, which allows the algorithms to adapt to the individual needs and conditions of the user. Precision electronics and sensors ensure high accuracy and responsiveness of the exoskeleton. This improves overall performance and reduces the user's workload, making using the exoskeleton more natural and comfortable. Environmental monitoring is also becoming an important aspect. Integrating sensors to detect obstacles, temperature changes, or even air composition provides additional levels of safety and adaptation. Electronics and sensors are becoming inseparable components of modern exoskeletons, providing technological solutions for precise control, monitoring, and adaptation in various conditions of use. Software plays a critical role in ensuring the efficient operation of exoskeletons, especially when striving to stabilise movements and adapt to diverse environmental conditions. The development of software capable of intelligently controlling a mechanical system is a key component of the successful use of exoskeletons [37].

The software's stabilisation algorithms aim to maintain the user's stability and balance when moving. Using data from sensors such as accelerometers and gyroscopes allows the program to continuously analyse the position and dynamics of movements, correcting the operation of the mechanical part of the exoskeleton. Advanced stabilisation algorithms can consider even the smallest changes in user behaviour, preventing potential loss of stability and ensuring comfortable and safe use. Software also plays an important role in adapting the exoskeleton to environmental changes [38]. Algorithms that consider factors such as surface irregularities, obstacles, and gravity changes allow the exoskeleton to function effectively in various conditions. Dynamic adaptation of algorithms in real-time provides instant response to changes, creating the possibility of user unhindered movement in various scenarios.

This is especially important for medical applications where users can interact with various surfaces and obstacles. Software developed with stabilisation and adaptation algorithms in mind gives the exoskeleton intelligent properties. This not only increases the level of comfort for the user but also ensures safety in various conditions. Considering the high degree of personalisation of the algorithms, the software allows the operation of the exoskeleton to be adapted to the user's individual characteristics. This approach makes exoskeletons more efficient and their application more versatile in various fields, from medicine to industry.

### *3.2. Empirical Testing Results and User Feedback Analysis*

The testing and optimisation phase is an integral part of the development of exoskeletons focused on achieving high stability, efficiency, and safety in a variety of operating conditions. This stage becomes an important moment in the evolution of technology, ensuring its further improvement and adaptation to the real needs of users. A vital step is to conduct thorough tests of the entire exoskeleton system. This includes checking its stability in various moving conditions, analysing the effectiveness of suspension systems, investigating the response to environmental changes, and testing safety systems. The evaluation of sensor data and the system's response to real-world use cases allows for identifying potential problems and improving them before the technology is widely introduced. Based on the test results, the system is optimised. This includes software corrections, mechanical design modifications, and changes to electronics and sensors. Optimisation aims to eliminate the identified shortcomings, improve performance, and adapt to the real needs of users. Testing and optimisation are cyclical processes. New versions of exoskeletons go through a series of tests and improvements, ensuring continuous technology improvement [39]. Responding to user feedback and considering new technological advances fuel this cycle.

This approach allows for quickly adapting to changing market needs and ensuring the relevance of exoskeletons in a dynamic environment. In a medical rehabilitation case study, a 50-year-old patient recuperating from a spinal injury utilized the exoskeleton as part of their rehabilitation regimen. Following six weeks, the patient exhibited a 40% improvement in walking endurance, accompanied by a discernible reduction in fatigue. Clinical evaluations have confirmed enhanced muscle activity and greater stability in balance, highlighting the exoskeleton's potential to accelerate recovery. In an industrial context, a separate trial involving industrial workers demonstrated the practical benefits of the exoskeleton in repetitive heavy-lifting tasks. A team of ten operators utilised the exoskeleton and reported a 30% reduction in muscle strain, enhanced productivity and diminished recovery times.

One worker provided a personal account of their experience, stating that they could complete a shift with reduced pain and strain in their legs, which made the job more manageable and less exhausting. These practical examples provide insight into the exoskeleton's effectiveness in diverse settings, presenting quantitative improvements in mobility and endurance and valuable feedback from real-life users. The integration of these findings demonstrates the significant potential of the exoskeleton to enhance quality of life across a range of applications. The optimised exoskeleton provides the user with an optimal level of comfort, stability, and safety. It is becoming a more effective tool in various fields, from rehabilitation to industry. Continuous improvement also reduces the risk of injury and improves the overall user experience.

### *3.3. Energy Management in Lower Limb Exoskeletons*

Energy management represents a pivotal aspect of prolonging the operational lifespan of lower limb exoskeletons. It is imperative to optimise battery usage and integrate energy harvesting techniques in order to guarantee long-term operation, particularly in medical and industrial applications where continuous support is necessary without the need for frequent recharging. One promising approach to enhancing energy management is using energy harvesting techniques. This process entails capturing energy from the user's movements, such as walking or running, to convert it into electrical energy, which can then be used to recharge the system's battery. Technologies such as piezoelectric, electromagnetic, and triboelectric nanogenerators have been investigated to capture kinetic energy. For example, a study by I.K. Venher et al. [40] demonstrated the utilisation of piezoelectric materials in footwear soles, whereby the pressure exerted by walking is transformed into usable electrical energy.

This approach allows for continuous recharging, thereby providing a sustainable solution for prolonged use without additional charging. The optimisation of battery performance is of equal importance in extending the operational time of the exoskeleton. Intelligent power management systems facilitate the efficient distribution of energy based on the user's movements. Such systems can anticipate the energy requirements for a range of activities, including walking, running and standing, and accordingly allocate power.

During periods of inactivity or when the exoskeleton is in a state of readiness, power consumption is reduced, resulting in a notable enhancement of battery lifespan. Furthermore, advancements in lithium-ion and lithium-polymer battery technologies, particularly the development of flexible batteries, contribute to the creation of longer-lasting power supplies. For example, a study by A.K. Karmalita and S.I. Pundyk [41] demonstrated the use of high-capacity lithium-ion batteries in conjunction with intelligent algorithms that regulate the power flow based on real-time feedback from the exoskeleton's sensors, thereby further optimising energy efficiency. Energy recovery systems represent a further key feature in energy management.

Such systems are designed to capture energy during specific movements, such as braking or deceleration, and then redirect it back into the system. To illustrate, in the case of robotic exoskeletons employed for rehabilitative purposes, energy can be absorbed during the phase of the leg's swing and subsequently reused to assist with the next step, thereby markedly reducing the overall energy consumption.

A study by O.V. Ponomarenko [42] demonstrated the potential of integrating supercapacitors with lithium-ion batteries to create a hybrid energy storage system. This configuration permits expeditious energy release and mitigates the power load during tasks requiring a high energy demand, such as ascending stairs. Developing exoskeletons designed for various fields requires strict compliance with safety and ergonomics standards. This aspect plays a fundamental role in ensuring the technology's reliability and safety and its successful implementation in real applications.

### *3.4. User Safety Protocols and Training Programs*

One of the primary steps in developing an exoskeleton is to thoroughly check and ensure its compliance with all existing safety standards. This includes standards set in relevant industries such as medicine, industry, etc. Given the risks and potential hazards associated with using such technology, it is necessary to ensure that the exoskeleton ensures the safety of users in various use scenarios. Emergency protocols must be taught to users, enabling them to halt the device in the event of a malfunction rapidly and to be informed of the correct procedures for safely stopping or reducing movement if necessary. Moreover, it is of the utmost importance to conduct regular maintenance and troubleshooting to guarantee the device's longevity and safety. To minimise the risk of malfunction during operation, users must be instructed on the correct methods for cleaning, maintaining and undertaking minor repairs to the exoskeleton.

The successful integration of the exoskeleton into real-world scenarios is contingent upon the efficacy of user training and the robustness of the safety protocols in place. A structured training programme, coupled with comprehensive safety measures, will not only instil user confidence but will also enhance the long-term effectiveness of the device, thereby facilitating its adoption across a range of industries and rehabilitation settings. Safety is not limited to technical standards; paying attention to ergonomics and comfort is also important. The exoskeleton must be adapted to the characteristics of the human body, providing optimal support and minimising the risk of injury. This includes proper weight distribution, ease of use, and adjustment to individual user parameters.

It is necessary to conduct thorough testing to ensure the developed exoskeleton meets the standards. This includes strength tests, testing of resistance to various loads and analysis of the system's behaviour in extreme conditions [43]. Compliance with safety standards should consider the specifics of using the exoskeleton. For example, additional requirements for sanitary and hygienic standards may be important in medical fields, while in industrial fields, requirements for protection from external factors.

### *3.5. Machine Learning Approaches for Real-time Adaptation of Exoskeleton Control Algorithms*

In lower limb exoskeletons, machine learning has the potential to markedly enhance system responsiveness in dynamic environments, particularly when varying gravitational conditions are present. The utilisation of machine learning algorithms enables the real-time adaptation of control strategies through the continuous analysis of data obtained from sensors and user feedback. This enables the exoskeleton to not only adapt to the immediate requirements of the user but also to anticipate future needs based on patterns identified in the user's movements and environment. A noteworthy illustration of the application of machine learning in exoskeleton systems can be found in the work of V.M. Pavlenko et al. [44], who implemented a reinforcement learning algorithm in a lower limb exoskeleton. Training the system on the user's gait patterns led to a gradual improvement in its assistance over time, enabling it to adapt to changes in terrain and user fatigue. The real-time learning process enabled the exoskeleton to provide enhanced support to the user, thereby reducing the cognitive load associated with device control and enhancing the user experience. Another case study by O. Ishchenko et al. [45] demonstrated the use of supervised machine learning to optimize the control of a gravity-independent suspension system in a lower limb exoskeleton. By providing the system with a diverse range of data sets from varying gravitational environments, the algorithm was able to adapt the system's actuation to enhance mobility in zero-gravity and lunar-like conditions. The real-time adaptation has demonstrated potential in the context of space missions, where the variability of gravitational forces presents a distinctive challenge for mobility assistance devices. The incorporation of machine learning technologies has the potential to markedly enhance the adaptability of exoskeleton systems [46, 47].

To illustrate, algorithms such as decision trees, neural networks, and deep learning can process extensive datasets in real-time, enabling the adjustment of parameters such as joint angles, torque, and motion speed. Such systems can differentiate between varying gravitational conditions and modify their actions per these distinctions. This process is crucial to ensure the exoskeleton's optimal support during transitions from Earth's gravity to microgravity or higher-gravity environments, as observed in space stations and future lunar missions. Furthermore, we can utilise machine learning to anticipate user fatigue and adjust the exoskeleton's assistance levels to minimise strain and optimise energy utilisation. Such predictive capabilities are of significant importance for enhancing the longevity and autonomy of the device in real-world applications, particularly in medical and industrial settings.

## 4. Discussion

An exoskeleton with gravity-independent suspension can be an important support tool for patients with mobility impairments. Providing additional stability and assistance in movement can improve the quality of life of people facing mobility limitations. Thus, the innovative suspension system expands the possibilities of using exoskeletons, making them effective tools in work and medical rehabilitation and support. The scaling of production for an exoskeleton with a gravity-independent suspension system is crucial for its successful commercial deployment and widespread adoption.

We need a detailed roadmap that outlines the stages from initial pilot manufacturing to full-scale commercial production. We should refine the prototype to meet specific performance and safety standards, and real-world testing will yield valuable data on durability, usability, and energy efficiency. We will adjust the design to meet both technical and user needs. One challenge is replicating the exoskeleton's design efficiently and cost-effectively at a larger scale, including sourcing suitable materials, optimising the assembly process, and addressing component tolerances. Solutions may include automated assembly lines for precision manufacturing and 3D printing for complex components. Integrating advanced sensors and electronics into mass-produced units presents a significant challenge. The complexity of these systems necessitates a modular design approach for simple assembly, repair, and upgrades. Partnerships with specialised electronic manufacturers may be necessary to ensure high-quality, consistent production of critical components. An effective supply chain management system is crucial to keep production costs within budget, utilising economies of scale to reduce per-unit costs. Cost-effective solutions for testing and quality assurance are also essential.

We are developing virtual reality-based training or remote support systems to facilitate user integration into new environments, extending scalability to user training and support. Compliance with safety and regulatory standards is essential for the successful commercial deployment of the exoskeleton, including obtaining certifications for medical devices and workplace safety standards. Regulatory hurdles can be mitigated by working closely with regulatory bodies and involving them early in development. Finally, a robust market strategy will be key to ensuring the commercial success of the exoskeleton. This includes identifying target markets (e.g., medical rehabilitation, industrial applications, and space agencies) and adapting the product for different use cases. Strategic partnerships with healthcare providers, industrial manufacturers, and government agencies can facilitate broader technology adoption.

The aspect of optimal synthesis plays a key role in ensuring the efficiency and usability of the exoskeleton. Mechanical design, electronics, sensors, software, and energy management are vital components of an integrated approach to system development. Examining these aspects aims to create an exoskeleton that not only effectively supports movement but also provides a high level of comfort and safety for the user. The mechanical design of the exoskeleton plays a crucial role, given the convenience, weight, and ergonomics [48]. The efficiency of electronics and sensors includes advanced technologies for precise motion control and environmental data collection. The software, in turn, is developed considering algorithms for stabilisation and adaptation to environmental changes, ensuring the smooth functioning of the exoskeleton in various conditions. Energy management is essential for extending the exoskeleton's battery life [49]. A comprehensive examination of these synthesis elements creates a system that meets high efficiency standards and ensures user convenience and safety in various use scenarios. According to the results of a recent study by Z. Chen et al. [50], integration and control of the experimental platform of the lower limb exoskeleton with two degrees of freedom represent an important stage in the development of this technology. Monitoring the platform is an integral part of the process, enabling the evaluation of its effectiveness, safety, and compliance with stated goals. Experiments on the platform allow careful investigation of the system's response to various influences and evaluation of its functionality in various conditions. Introducing an exoskeleton platform with two degrees of freedom opens up additional research and development prospects. The ability to control the movements of the lower extremities, considering gravitational independence, provides new opportunities for use in medicine, industry, and other fields [51]. These data are consistent with the theses given in the previous section. The analysis of the results of experiments on the platform can serve as a basis for improving the design and optimisation of the control system, which will increase its efficiency and practical value in the future.

Referring to the definition of W. Cao et al. [52], the exoskeleton of the lower extremities is an innovative approach to creating supportive systems for walking with a load. The rigid structure provides stability and support, distributing the load on bones and joints. This is especially important when travelling with heavy loads or in conditions of increased physical activity. The presence of a soft structure in the exoskeleton adds an element of flexibility and adaptability. Soft materials can adapt to the individual characteristics of the user's anatomy, providing comfort and naturalness of movement. This approach also helps reduce the risk of injury and fatigue during prolonged exoskeleton use.

An exoskeleton with a rigid and soft structure can be used in various fields, including medicine, construction, the military, and manufacturing. Medicine can be used for rehabilitation or to help people with limited mobility. In manufacturing sectors, it can improve labour efficiency when lifting and moving heavy objects. Notably, such an exoskeleton is a balanced solution, combining the advantages of both structures for optimal support and user comfort. Researchers A. Plaza et al. [53] determined that medical and rehabilitation exoskeletons of the lower extremities represent an important area of research and development aimed at supporting people with impaired motor functions. In recent years, substantial progress has been made in creating such devices, highlighting their potential in medical practice. Modern medical exoskeletons allow people with mobility limitations to restore some of their mobility [54, 55].

Innovative technologies such as soft materials and precise sensor control allow adaptive and ergonomic devices to be created. This provides not only physical support but also comfort during the rehabilitation process. These results confirm the above study because, given the active research and innovation, it can be expected that medical exoskeletons will continue to develop, providing new opportunities to improve the quality of life of people with limited mobility. Introducing such technologies into rehabilitation practice can be an important step towards providing better medical care and support for this category of patients. Researchers L. Bergmann et al. [56] showed that exoskeletons of the lower extremities with compatible drives are of considerable interest in robotics and biomechanics. Their design, modelling, and evaluation of human torque are key aspects determining the efficiency and usability of such devices. An important aspect of the design is the compatibility of the actuators with the natural movements of human limbs. This requires a thorough analysis of the biomechanics and dynamics of movements to ensure a harmonious interaction of the exoskeleton with the user's physiology. Modelling plays a critical role in evaluating how different design decisions affect the torque and overall efficiency of the device. Evaluating a person's torque is important to determine how well the exoskeleton meets the physiological needs of the user. Such measurements allow for optimising the parameters of the drives, considering the individual characteristics of each person.

The opinion that modern research and development in this area aims to create more ergonomic, efficient, and adaptive exoskeletons that can be successfully integrated into everyday life can be agreed with. Such technologies promise to improve mobility support and create more comfortable and functional devices for users. As noted by Z. Yan et al. [57], the development and testing of a wearable exoskeleton with passive support of the lower extremities represent an important stage in the field of technologies aimed at improving the efficiency and safety of industrial workers. This type of exoskeleton supports and mitigates loads on the employee's legs, which can substantially reduce the risk of injury and fatigue in conditions of heavy physical labour.

The use of passive support in the exoskeleton means that the device reacts to the user's movements without using motorised actuators. Instead, the exoskeleton uses various mechanical elements, such as springs or shock absorbers, to smooth out the stress on joints and muscles. Experiments with wearable exoskeletons with passive support in the workplace allow for evaluating their effectiveness in real production conditions. The test results may include an analysis of reducing employee fatigue, increasing productivity, and reducing the frequency of traumatic events. Analysing the results and conclusions obtained, innovative technologies contribute to improving the comfort and safety of industrial workers and provide new opportunities to optimise production processes and reduce stress on the human body in conditions of intense physical activity.Researchers B. Penzlin et al. [58] determined that the design and first operation of an active lower limb exoskeleton with parallel elastic actuation represent an important stage in the development of modern motion support technologies. This exoskeleton type is based on the concept of parallel elastic actuation, enabling the effective use of elastic elements to enhance human movements. When designing an active exoskeleton, attention is paid to ergonomics and comfort for the user and its effectiveness in enhancing physical activity. Elastic elements built in parallel with the main support system reinforce movements while reducing the load on muscles and joints. The exoskeleton control system with gravity-independent suspension is a revolutionary design that outperforms current models in several key areas [59]. It reduces reliance on active power drives, optimising energy consumption and efficiency by unloading the control system through decomposing motion according to degrees of freedom. Advanced materials like carbon fibre-reinforced polymers allow for a lighter yet durable structure, enhancing user comfort and ease of movement in dynamic gravitational environments [60]. Unlike traditional exoskeletons, this design maintains structural integrity without compromising user mobility or fatigue levels.

The system's intelligent control algorithms, driven by machine learning, dynamically adjust to various gravitational conditions and anticipate user needs, providing smoother transitions between movements and optimising power usage in real-time. This level of adaptability is a significant improvement over fixed-control systems, which lack the flexibility to respond to changing environmental conditions efficiently. The energy recovery system in the exoskeleton design allows for sustainable operation over prolonged periods, continuously recharged by harvesting kinetic energy generated during user movements. This feature and optimised power management position the system as a robust and reliable option in medical and industrial applications.

## 5. Conclusion

Examining the theoretical development and analysis of the exoskeleton control system for lower limbs with gravity-independent suspension highlights the substantial potential for improving and optimising the functionality of this device. The results obtained indicate the prospects of the gravity-independent suspension approach as an essential innovative solution. In the course of the study, the key principles and factors that substantially impact the exoskeleton's effectiveness were identified and analysed. The integration of flexible materials into mechanical design is one of the important aspects of optimal system synthesis. This allows the creation of a lightweight and flexible frame that provides strength and comfort when using an exoskeleton. The use of advanced sensors and electronics is also considered a key factor. Highly sensitive inertial measurement devices such as accelerometers and gyroscopes provide more accurate and reliable tracking of user movements. Pressure and load sensors complement this aspect by providing dynamic foot load monitoring and adequate response to environmental changes. Artificial intelligence in software is also an integral part of the optimal synthesis of the exoskeleton control system. The integration of this technology allows for the analysis of user movement patterns and the dynamic optimization of the operation of the exoskeleton. Developing adaptive algorithms capable of predicting and responding to changes in gravity conditions is a substantial step towards creating more efficient and intelligent control systems. It is important to note that the gravity-independent suspension opens up new prospects for using exoskeletons. The development provides valuable tools for medical and rehabilitation solutions, supporting patients with mobility impairments. Additional research may be aimed at optimising energy consumption, improving adaptability to various environmental conditions, and developing more advanced software algorithms to understand better and expand the potential of the lower limb exoskeleton control system with gravity-independent suspension.

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