ABSTRACT

dissertation work of doctoral student Zhetenbayev Nursultan on the topic «Design of the exoskeleton of ankle joint with artificial muscles», nominated for the degree of Doctor of Philosophy (PhD) in the specialty 6D071600 – «Instrument making».

The relevance of the work. The prevalence of individuals with limited mobility is experiencing annual growth, thereby exerting a pronounced influence on the quality of life and necessitating a heightened reliance on external assistance. The application of physical therapy is an imperative measure in addressing these conditions. The integration of robotic apparatus enables the facilitation of rehabilitative processes via meticulously controlled exercise regimens.

Shortcomings inherent in contemporary robotic rehabilitation solutions have underscored the imperative to develop cost-effective devices capable of rendering rehabilitation interventions to patients afflicted by limb injuries. In this regard, the utilization of an ankle joint exoskeleton, comprising artificial muscles, has proven to be efficacious in fostering the rehabilitation of ankle joint functions among post-injury patients. Furthermore, these artificial muscles can function as intermediaries between the human body and sensors, thereby presenting an avenue for the development of a novel generation of prosthetic devices.

The ankle joint exoskeleton, equipped with artificial muscles, holds significant relevance across multiple domains, notably within the spheres of healthcare, rehabilitation, and sports performance.

The objective of this study is to explore the design and advancement of an ankle exoskeleton through the integration and refinement of artificial muscle technology.

The research objectives are as follows:

1. To investigate existing ankle joint exoskeletons, examining their structural configurations, technical components, and identified challenges.
2. To analyze the anatomical structures from which exoskeleton components are derived, considering their biomechanical characteristics.
3. To identify and select appropriate artificial muscle technologies in accordance with the exoskeleton's design requirements.
4. To develop a computer-based model of the exoskeleton device.
5. To realize the creation of an experimental prototype of the exoskeleton system.
6. To conduct comprehensive testing and refinement of the exoskeleton, encompassing evaluations under varying loads and environmental conditions, to ensure compliance with established criteria and efficacy in enhancing mobility and quality of life.

The object of this study is an ankle joint exoskeleton designed for rehabilitation purposes.

The subject of the study involves the specific components and aspects related to the prototype of the ankle exoskeleton with artificial muscles. These include:

1. Biomechanics of the Ankle Joint: This research focuses on comprehending the biomechanical characteristics of the ankle joint, encompassing aspects such as the range of motion, force requirements for various movements, and the coordination of muscles during ankle joint functions.
2. Artificial Muscles: The investigation is dedicated to the design and optimization of artificial muscle technologies, which may include pneumatic, hydraulic, and electric systems, tailored for integration into the exoskeleton.
3. Control Systems: This facet of the study pertains to the development and enhancement of control systems for the exoskeleton, encompassing the integration of sensors, processors, and power supply mechanisms.
4. Clinical Studies: The research undertakes clinical trials involving individuals undergoing rehabilitation, with the aim of assessing the exoskeleton's effectiveness in terms of improving mobility and enhancing the quality of life for the subjects.
5. Performance Enhancement: This segment of the study is designed to evaluate the exoskeleton's efficacy in augmenting performance during rehabilitation, considering aspects such as speed, agility, and endurance improvements.

Research methods. the tasks are solved using the methods of theoretical and applied mechanics, the theory of robotic systems, computational mathematics, and control systems.

The reliability of the results obtained is based on the consistency and completeness of the initial assumptions, the correct application of the methods of theoretical and applied mechanics, the coincidence of the results of theoretical research with experimental data and the practical implementation of the proposed methodology for analyzing commands as part of the layout of the ankle joint control system.

The scientific novelty of this study is underpinned by the following key contributions:

1. Optimal Utilization of Exoskeletal Devices with Artificial Muscles: The research delves into an exhaustive examination of existing exoskeletons and their associated control systems. As a result, it has identified and proposed an optimal solution for harnessing exoskeletal devices equipped with artificial muscles.

2. Enhanced Efficiency of Exoskeletons with Artificial Muscles: The study has rigorously investigated the design of exoskeletons incorporating artificial muscles and has innovatively devised new solutions to augment the overall efficiency of these devices. A particular focus has been placed on the thorough analysis of artificial muscle technologies.

3. Safety-Compliant Exoskeleton with Artificial Muscles: The scientific breakthrough lies in the creation of an ankle exoskeleton integrated with

artificial muscles, meticulously engineered to adhere to stringent safety standards. This innovation extends to the selection of components and electric drives, ensuring full compliance with electrical safety requirements. The resulting exoskeleton serves to significantly improve the mobility and quality of life for individuals with musculoskeletal disorders and those in need of rehabilitation.

4. Controlled Resistance and Healing Promotion: The incorporation of artificial muscles within the exoskeleton introduces a pioneering approach to providing controlled resistance and aiding in ankle recovery and muscle strengthening. The integration of sensors and advanced control systems permits precise and individualized manipulation of artificial muscles, representing a noteworthy feature in exoskeletal design.

5. Adaptability for Varied Mobility Disorders: The exoskeleton is distinguished by its adaptability, catering to the unique needs of individuals with diverse mobility impairments. This individualized approach facilitates personalized rehabilitation and heightens athletic performance. Moreover, the exoskeleton's adjustability in response to the evolving stages of the healing process allows for gradual restoration and fine-tuning of the resistance and assistance offered by the artificial muscles.

6. Holistic Exoskeleton Design: In essence, the scientific novelty of this study resides in the comprehensive development of a novel exoskeleton design, incorporating artificial muscles and a sophisticated control system. This innovation holds significant promise for advancing mobility, rehabilitation, and athletic prowess, representing a remarkable leap in the field of exoskeletal technology.

Practical significance and results:

The proposed ankle exoskeleton designed for rehabilitation purposes can potentially become the basis for the development of innovative control systems. The electric drive, optimized for the needs of ankle rehabilitation, is a versatile and adaptable solution that can be used to improve control systems in various other applications. Its applicability goes beyond exoskeletons themselves, opening opportunities for the creation of new and advanced control systems in various areas where precise and fast-responding control mechanisms are required. The integration of this electric drive technology into control systems opens the way to the development of more efficient, efficient, and customized solutions for a wide range of applications.

Conclusions proposed for protection:

1. A mathematical model has been developed that characterizes the dynamics of the movement of the ankle exoskeleton with special consideration for the linearity within the electric drive component. This model provides a framework for understanding and predicting the behavior of the system.

2. The creation of a functional prototype of an ankle exoskeleton with artificial muscles and an integrated control system meets the functional prerequisites necessary to increase mobility and accelerate the healing process. This prototype demonstrates the feasibility of the proposed design.

3. A comprehensive biomechanical analysis of the ankle joint was performed to determine the parameters of the exoskeleton functionality, including the range of motion, required strength and other functional criteria. This analysis forms the fundamental basis for designing and evaluating the effectiveness of the exoskeleton.

4. Experiments and trials have played an important role in optimizing the performance of artificial muscles, ensuring that they provide the necessary resistance and assistance to the ankle joint. This process has improved the functionality of the key components of the exoskeleton.

5. The development of an advanced control system, including sensors for detecting the movement of the ankle joint, a processor for real-time control of artificial muscles and a reliable power supply, marks a significant achievement in ensuring accurate and fast operation of the exoskeleton.

6. Tests of the exoskeleton under various loads and different conditions have confirmed its compliance with the established requirements and effectiveness in improving the mobility and quality of life of people with reduced mobility. These tests confirm the practical usefulness of the device.

7. Creation of an effective exoskeleton design capable of improving the mobility and quality of life of people with mobility impairments, facilitating treatment and rehabilitation, as well as improving athletic performance. The research contributes to the development of assistive technologies and their potential to positively influence the lives of those in need.

Approbation of research results. The main results of the work are presented in 1 scientific journal and 6 international and scientific and technical conferences, including:

- Nursultan Zhetenbayev., Gani Balbayev., Algazy Zhauyt., Beibit Shingissov., «Design and Performance of the New Ankle Joint Exoskeleton», International Journal of Mechanical Engineering and Robotics Research Vol. 12, № 3, May 2023 DOI: 10.18178/ijmerr.12.3.151-158.
- «IFToMM Asian Mechanisms and Machine Science Conference – 2021» (December 15-18, Hanoi University of Science and Technology, Vietnam).
- «55th International Conference on VIBROENGINEERING – 2022» (April 21, 2022, in Almaty, Kazakhstan).
- «2022 International Conference on Communications, Information, Electronic and Energy Systems», CIEES 2022, (24 – 26 November 2022, Veliko Tarnovo, Bulgaria).
- «The Joint International Conference of the 13th IFToMM International Symposium on Science of Mechanisms and Machines (SYROM 2022) and the XXV International Conference on Robotics (ROBOTICS 2022) » Iasi, Romania (November 17 - 18, 2022,).
- «8th International Workshop on New Trends in Medical and Service Robots, MESROB 2023 Craiova» 7-10 June 2023.

The structure and scope of the dissertation work. The work consists of an introduction, four chapters, a conclusion, a list of references and 1 appendix.

The total volume of the work is 129 pages, the work contains 52 figures, 10 tables, a list of literature from 122 titles.

The dissertation research is a comprehensive exploration of the design and development of an ankle exoskeleton for rehabilitation. The research is structured as follows:

Introduction: The introduction outlines the research's relevance, objectives, subject matter, tasks, methods, scientific novelty, and practical significance. It also highlights the testing and publication of research results.

Chapter 1: This chapter conducts an extensive review of the contemporary landscape of exoskeleton design in the rehabilitation field. It identifies emerging trends and envisions potential future directions. The chapter also surveys various artificial muscle technologies used in ankle exoskeletons, including pneumatic and hydraulic drives, sequential elastic drives, and electric linear drives. Among these, electric linear actuators are chosen for their precision, efficiency, and seamless integration into the complex exoskeleton architecture.

Chapter 2: In this chapter, the research focuses on modeling and simulation of the ankle exoskeleton using SolidWorks software with the Motion Simulation add-in. The Somov-Malyshev formula is employed to propose the kinematics of the mechanism within the spatial kinematic structure. A mathematical model of the ankle exoskeleton's movement dynamics is developed, considering the linearity in the electric drive.

Chapter 3: This chapter details the selection of PLA (Polylactic Acid) as the prototype material for the ankle exoskeleton. It also provides an overview of the electronics integrated into the exoskeleton, along with the description of its control algorithm and software.

Chapter 4: Chapter 4 delves into the outcomes of experimental studies and functional testing of the ankle exoskeleton. The specific movements analyzed include ankle joint mobility, foot flexion, and foot extension.

Conclusion: The conclusion summarizes the results and key findings from the dissertation research. It also outlines future for further work and development within the chosen research direction.

This dissertation research demonstrates a comprehensive exploration of ankle exoskeleton design, encompassing theoretical modeling, practical prototype development, and functional testing. It signifies an important contribution to the field of rehabilitation and assistive technology, with the potential to enhance mobility and quality of life for individuals with musculoskeletal disorders.