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"Development and Investigation of an Electromechanical Drive with an Adaptive Control System for an Ankle Joint Exoskeleton"

Dissertation submitted for the degree of
Doctor of Philosophy (PhD)
in the specialty
6D060300 – Mechanics

ABSTRACT

Relevance of the Research Topic. Musculoskeletal diseases and injuries are currently among the most pressing challenges in global healthcare. According to the World Health Organization (WHO), stroke, neuro-orthopedic disorders, sports injuries, and age-related limitations in motor activity have a direct impact on patients' quality of daily life. In particular, ankle joint injuries may lead to impaired walking function and require comprehensive rehabilitation.

Along with conventional physiotherapy methods, the use of robotic exoskeletons opens up new opportunities for telerehabilitation and home-based rehabilitation. The main advantages of such devices include accurate reproduction of movements, uniform distribution of loads, and the ability to adapt to the individual biomechanical characteristics of a patient.

However, a number of existing exoskeletons are expensive, structurally complex, and designed primarily for clinical environments, which limits their widespread accessibility. Therefore, the development of a lightweight, flexible, remotely controlled ankle exoskeleton that meets biomechanical requirements is a relevant scientific and engineering challenge.

The relevance of this work lies in the development of an exoskeleton system capable of reproducing the physiological range of motion of the ankle joint, equipped with safety features and supporting remote control via a Bluetooth module. The proposed device enables rehabilitation not only in clinical settings but also at home, thereby contributing to an improvement in patients' quality of life and increasing the accessibility of rehabilitation procedures.

Aim of the Research. The aim of the research is to design an electromechanical drive for an ankle joint exoskeleton, develop an adaptive control system, and investigate its motion efficiency during the rehabilitation process.

Object of the Research. An active rehabilitation exoskeleton designed to reproduce human ankle joint movements in accordance with biomechanical requirements.

Subject of the Research. Electromechanical drives and adaptive control systems of the ankle joint exoskeleton.

Research Objectives. In accordance with the stated aim, the following objectives were formulated:

- to design an ankle joint exoskeleton based on an analysis of the anatomical structure, range of motion, and clinical limitations of the ankle joint;

- to synthesize the programmed motion of the ankle joint exoskeleton based on the developed model;
- to develop a dynamic model of the motion of the electromechanical drives of the ankle joint exoskeleton;
- to investigate adaptive control of the electromechanical drives of the ankle joint exoskeleton;
- to develop an ankle joint exoskeleton prototype, conduct experimental studies, and evaluate its motion efficiency during rehabilitation.

Research Methods. Analytical methods, biomechanical analysis, and mathematical modeling were employed in the research. Equations of motion and dynamic models were developed to describe the kinematics and dynamics of the ankle joint exoskeleton.

Computer modeling was performed using SolidWorks 3D CAD, which enabled the design of the structural components of the exoskeleton and verification of their kinematic compatibility.

Simulation studies were carried out in the MATLAB/Simulink environment to investigate the dynamic behavior of the system and verify the adaptive control algorithms.

In addition, experimental studies were conducted using the developed exoskeleton prototype. Its motion parameters, control accuracy, and effectiveness in the rehabilitation process were evaluated.

Scientific Novelty of the Research

- a novel structural solution for an electromechanically actuated exoskeleton that takes into account the biomechanical characteristics of ankle joint motion has been proposed;
- a kinematic model ensuring physiological ankle joint motion has been developed for the proposed mechanism;
- a dynamic model of the electromechanical drives of the proposed exoskeleton has been developed and its parameters have been determined;
- an adaptive control algorithm ensuring accurate and stable motion has been developed;
- an experimental prototype has been developed based on the proposed model, and its effectiveness has been experimentally validated.

Theoretical and Practical Significance of the Research. The developed exoskeleton enables restoration of ankle joint movements following injuries or in patients with neurological disorders. The proposed control algorithms ensure stable and accurate motion in real time. The developed prototype is adapted for application in medical rehabilitation centers. The research results may provide a basis for the further development of medical robotics in Kazakhstan.

Main Provisions Submitted for Defense

- an exoskeleton structure corresponding to the physiological and biomechanical patterns of ankle joint motion;
- kinematic and dynamic models of the exoskeleton and mathematical relationships ensuring motion accuracy;

- an adaptive algorithm for controlling the electromechanical drives and its stability properties;
- experimental results confirming the motion efficiency of the proposed exoskeleton prototype during the rehabilitation process.

Reliability and Validity of the Scientific Results of the Dissertation. The validity of the scientific results presented in the dissertation is ensured through the application of methods of classical mechanics, biomechanics, and automatic control theory. MATLAB/Simulink and SolidWorks software packages were used in the research to develop the kinematic and dynamic models of the exoskeleton.

The reliability of the obtained scientific results was confirmed by experimental studies conducted using the developed exoskeleton prototype. The good agreement between the MATLAB/Simulink simulation results and the experimental results confirms the correctness of the proposed mathematical model and adaptive control algorithm.

Relationship of the Research Results to Research Program Plans. The presented results were obtained within the framework of the program-targeted funding project of the Ministry of Science and Higher Education of the Republic of Kazakhstan, BR24992820**,** "Innovative Medical Technologies and Devices for Improving Surgical Interventions in Prosthetics and Rehabilitation in the Field of Orthopedics and Medical Rehabilitation" (Contract No. 376 dated October 1, 2024).

The author is also the Principal Investigator of the Zhas Galym grant project AP22688590, "Investigation of the Dynamics of Robotic Manipulator Drive Control."

Approbation of the Research Results

The main results of the dissertation were presented at the following international and national scientific and technical conferences and were also published in reputable scientific journals:

1. Ozhiken A.K., Rakhmetova P.M. Development of a Mathematical Model for Adaptive Control of a Robotic Manipulator // Proceedings of the International Satpayev Readings "Scientific Heritage of Shakhmardan Yessenov." – 2017. – pp. 626–629.
2. Ozhiken A., Ivanov K., Gonzalez-Cruz C.A., Ceccarelli M., Cafolla D. Design and Experiences of a Planetary Gear Box for Adaptive Drives // EuCoMeS 2018. Mechanisms and Machine Science. Vol. 59. Springer. DOI: 10.1007/978-3-319-98020-1_33.
3. Ozhiken A.K., Rakhmetova P.M. Investigation and Development of Motion Dynamics of Adaptive Control Systems for a Robotic Manipulator // International Scientific and Practical Conference "Current Problems of Informatics, Mechanics and Robotics." – Almaty, 2018. – p. 124.
4. Tuleshov A., Ozhiken A. et al. Modeling the Dynamics of a Heavy-Duty Mobile Robot Based on Gauss's Principle of Least Constraint // Journal of Applied and Computational Mechanics. – 2025. – 11(4). – pp. 946–960. DOI: 10.22055/jacm.2024.47902.4833. *(Scopus Q1).*

5. Ozhiken A.K., Tuleshov A.K. et al. Adaptive Motion Control System for a Manipulator // Bulletin of the National Engineering Academy of the Republic of Kazakhstan. – 2025. – No. 1(95). – pp. 160–169. DOI: 10.47533/2025.1606-146X.17. *(KOKHBO).*

6. Ozhiken A.K., Tuleshov A.K. et al. Development of a High-Robustness Adaptive Control System for a Manipulator// Bulletin of KazATK. – 2025. – No. 137(2). – pp. 133–141. DOI: 10.52167/1609-1817-2025-137-2-133-141. *(KOKHBO).*

7. Sergazin G., Ozhiken A. et al. Development of an Ankle Exoskeleton: Design, Modeling, and Testing // Sensors. – 2025. – 25(7):2020. DOI: 10.3390/s25072020. *(Scopus Q1).*

8. Ozhiken A., Sergazin G. et al. Research and Experimental Testing of a Remotely Controlled Ankle Rehabilitation Exoskeleton Prototype // Sensors. – 2025. – 25(21):6784. DOI: 10.3390/s25216784. *(Scopus Q1).*

9. Karasheva M., Ozhiken A. et al. Sensor-Driven Control Strategies for Post-Stroke Shoulder Rehabilitation Exoskeletons: A Systematic Review // MethodsX. – 2025. DOI: 10.1016/j.mex.2025.103648. *(Scopus Q1).*

Author's Personal Contribution. The main scientific results and conclusions presented in the dissertation were obtained with the direct participation of the author and are based on research independently carried out by the author.

The author developed the structural solution for the ankle joint exoskeleton, constructed its kinematic and dynamic mathematical models, developed the adaptive control algorithm, and performed simulations in the MATLAB/Simulink environment. In addition, the author directly participated in the design and development of the experimental exoskeleton prototype, implementation of the control system, structural strength analysis in SolidWorks, and organization and execution of experimental studies.

In the scientific publications prepared in co-authorship, the author made a major contribution to the literature review, development of mathematical models, execution of experimental studies, processing and analysis of the obtained results, and preparation of scientific publications.

Implementation and Application of the Research Results

The lower-limb exoskeleton prototype developed with the participation of the author is used in the educational process at Satbayev University and is currently undergoing testing at City Clinical Hospital No. 4 in Almaty.

Structure of the Dissertation. The scientific aim and objectives set in the dissertation have been fully achieved. The dissertation consists of a title page, normative references, a list of abbreviations, an introduction, four chapters, a conclusion, a list of references, and appendices.

Brief Description of the Dissertation Chapters

Chapter One provides an analysis of the current state of development of rehabilitation exoskeletons for the ankle joint. The anatomical and biomechanical characteristics of the ankle joint, modern types of exoskeletons and their actuators,

remotely controlled rehabilitation technologies, and types of electromechanical drives are considered.

Chapter Two addresses the design of the ankle joint exoskeleton. The biomechanical requirements for the exoskeleton are defined, and its kinematic and dynamic mathematical models are developed. In addition, a programmed control algorithm is proposed, an adaptive control system for the electromechanical drive is developed, and dynamic simulations are performed in MATLAB/Simulink.

Chapter Three describes the exoskeleton design, its main components, and the control system. The operating principle of the screw drive is substantiated and its advantages are presented. In addition, structural strength analysis is performed using SolidWorks Simulation.

Chapter Four presents experimental studies of the adaptive control system of the electromechanical drive and describes the experimental test bench. The experimental results are compared with the MATLAB/Simulink simulation results, and the effectiveness of the proposed control system is evaluated.

The concluding section of the dissertation summarizes the main scientific results of the conducted research and presents the theoretical and practical conclusions.