



UDC 004.89/004.94

IRSTI 50.30.31

[https://doi.org/10.53364/24138614\\_2026\\_40\\_1\\_22](https://doi.org/10.53364/24138614_2026_40_1_22)

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### ELBOW EXOSKELETON FOR PRONATION-SUPINATION MOTION: MODELING AND PROTOTYPE TESTING

**Abstract.** *This paper presents the design and experimental evaluation of an exoskeleton device intended for the rehabilitation of the elbow joint's pronation/supination motion. Accurately and safely performing this type of movement remains one of the main technical challenges in rehabilitation exoskeletons, as it involves complex biomechanical interactions and rotational motion of the forearm bones. Within the scope of the project, a CAD model with two degrees of freedom (DOF) was developed in SolidWorks. A physical prototype was then fabricated, and laboratory testing was conducted for one DOF – the pronation/supination motion. The accuracy of motion execution was recorded using an IMU sensor, and control performance was evaluated.*

*The proposed device is intended for use in the rehabilitation process of patients with neurological disorders, including restoring neuromotor functions after stroke and correcting elbow joint contractures. Experimental results demonstrate the suitability of the device for rehabilitation applications.*

**Keywords:** *elbow exoskeleton, pronation-supination, rehabilitation robotics, CAD model, IMU sensor, 2 DOF exoskeleton.*

#### Introduction.

In recent years, there has been a growing interest in the development of robotic exoskeletons for upper limb rehabilitation, particularly for restoring functions of the elbow and wrist joints. The elbow joint plays a key role in ensuring precision and freedom of arm movements during daily and professional activities, while the ability to perform forearm pronation–supination is a critical component of functional motor control [1].

The aim of this study is to present a comprehensive approach to the development of an active elbow exoskeleton with two degrees of freedom (DOF) for pronation–supination movement, including anthropometric analysis, mathematical and CAD modeling, prototype fabrication, and experimental evaluation.

To justify the chosen technical solutions, a detailed analysis of existing robotic devices used for wrist and elbow rehabilitation was carried out. These devices are classified according to their number of degrees of freedom, types of implemented movements, actuation mechanisms, control methods, feedback systems, experimental assessment strategies, safety requirements, and the inclusion of modern technologies such as gamification and artificial intelligence.

Early-generation upper-limb and wrist rehabilitation systems were extensively described in several foundational studies [1], [2], [3], [4], [5], [6], [7], which include structural design approaches, pilot clinical evaluations, and early attempts at multi-DOF human–robot interaction.

More advanced designs including impedance-controlled devices, tendon-driven mechanisms, and soft robotic orthoses are presented in later studies [8], [9], [10], [11], [12], [13], [14], [15], demonstrating improvements in control safety, portability, and clinical applicability.

A comparative summary of these devices is presented in Table 1, allowing for systematization of accumulated knowledge and identification of key design parameters for the development of a custom elbow exoskeleton.

Table 1 - Comparative characteristics of wrist and elbow rehabilitation devices

№	Device Name	DOF	Types of Movements	Control Characteristics	Institution	Notes
1	MIT Wrist Robot	3	Flexion/Extension, Pronation/Supination, Abduction/Adduction	Force sensor, direct control	MIT	Commercial version available
2	Tactile Handle	2	Open/Close, Pronation/Supination	Simple design	National University of Singapore	Functional hypothesis proposed
3	RiceWrist	3	FE, RU, PS	Impedance control	Rice University	High torque capabilities
4	OpenWrist	4 (1 passive)	Full wrist motion range	Improved design	Rice University	Extended workspace
5	UHD	3	FE, PS, RU	Joint sequence	Not specified	Enables isolated motion
6	IIT Genova	3	FE, RU, PS	Active control	IIT Genova	Expanded range of active motion
7	SCRIPT 1	1	Flexion/Extension	Passive device	University of Sheffield	Requires neurological supervision
8	Harvard Device	2	FE, PS	Pneumatic actuators	Harvard University	Assessed ROM and torque
9	WRES	3	FE, RU, PS	Not specified	Not specified	Exoskeleton-type device
10	WReD	1	Flexion/Extension	Exoskeleton	Kyushu University	Simple configuration
11	CR2-Haptic	1	Trains 3 types of movement	Reconfigurable mechanism	Not specified	Portable device
12	2-Linear Actuator Exo	2	FE, RU	Spring elements	Not specified	High flexibility, low accuracy
13	Force Sensor + 3DOF	1+	Flexion/Extension	Force sensor + extended features	Not specified	Improved human–robot interaction
14	Berlin Robot	1	Flexion/Extension	Bilateral therapy	Free University of Berlin	Mirror movement
15	UFU Prototype	1	FE (Impedance)	Impedance control	UFU	Low cost (~1000 USD)

Despite the significant progress achieved in the development of upper-limb rehabilitation exoskeletons, several practical challenges remain unresolved. Many existing systems focus either on complex multi-degree-of-freedom architectures with increased mechanical complexity and cost, or on simplified single-DOF solutions with limited adaptability and experimental validation. In particular, pronation–supination motion of the elbow joint remains insufficiently explored as a standalone functional movement, despite its critical role in daily activities and post-stroke motor recovery.

The analysis made it possible to define the requirements for the design of a custom elbow exoskeleton with two degrees of freedom. In this context, the present study aims to bridge the gap between conceptual multi-DOF design and practical experimental validation by proposing a modular elbow exoskeleton architecture. The contribution of this work lies in the combined development of a two-DOF CAD concept and a one-DOF physical prototype, enabling safe and controlled laboratory validation of the pronation–supination mechanism.

The paper further details the steps involved in building the kinematic and mathematical models, creating the CAD model, fabricating the prototype, and conducting experimental tests to validate the functionality and effectiveness of the proposed solution for rehabilitation applications. The study emphasizes an engineering-oriented workflow, integrating simplified dynamic modeling, modular mechanical design, and IMU-based experimental evaluation to assess motion accuracy and repeatability.

It should be noted that the present study focuses on the preliminary engineering validation of the proposed exoskeleton prototype. Therefore, experimental tests were conducted under no-load conditions and without direct interaction with the human limb. Biomechanical effects, such as muscle resistance and subject-specific variability, are considered beyond the scope of this work and will be addressed in future studies involving ethical approval and clinical supervision.

#### **Materials and methods.**

In this study, an exoskeleton device for the pronation–supination motion of the elbow joint was developed. A CAD model with two degrees of freedom (flexion/extension and pronation/supination) was designed using the SolidWorks environment. The prototype was fabricated using Fused Deposition Modeling (FDM) 3D printing technology with PLA material, and equipped with a servo motor, cable-driven mechanism, and an Arduino Nano microcontroller.

Experimental testing was conducted for only one degree of freedom the pronation, supination motion. To evaluate motion accuracy, an IMU sensor (MPU6050) was used to record angular data in real time. The system's repeatability and accuracy were assessed by comparing the measured data with the motor command inputs.

#### *CAD Model and Physical Prototype of the Exoskeleton*

The mechanical structure of the exoskeleton was designed using the SolidWorks software. The CAD model illustrates the overall architecture of the device, including the mechanisms responsible for the two primary elbow joint movements flexion/extension (FE) and pronation/supination (PS) as well as the layout of actuators and cable-driven components. The design supports two degrees of freedom (2 DOF), allowing for the execution of complex upper limb movements for rehabilitation purposes. The model consists of three main components: a shoulder mount, a rotational mechanism block, and a forearm support. During the design process, ergonomics, weight, and user comfort were carefully considered.

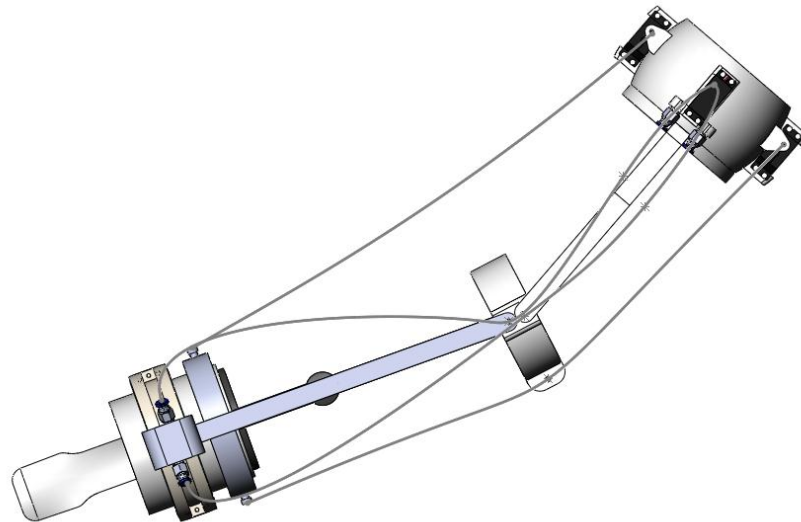


Figure 1 – CAD model of the exoskeleton developed in SolidWorks (2 DOF: FE and PS motions)

Figure 2 shows the physical prototype of the exoskeleton fabricated using 3D printing (FDM method) with PLA material. This initial prototype implements only one degree of freedom – pronation/supination (1 DOF). The device is equipped with a servo motor, cable-driven transmission, and an Arduino Nano microcontroller. The motor torque is transferred to the rotational module through cables, enabling controlled pronation/supination motion of the elbow joint. The prototype was designed in a modular fashion to facilitate experimental testing and future integration of a second DOF (flexion/extension).

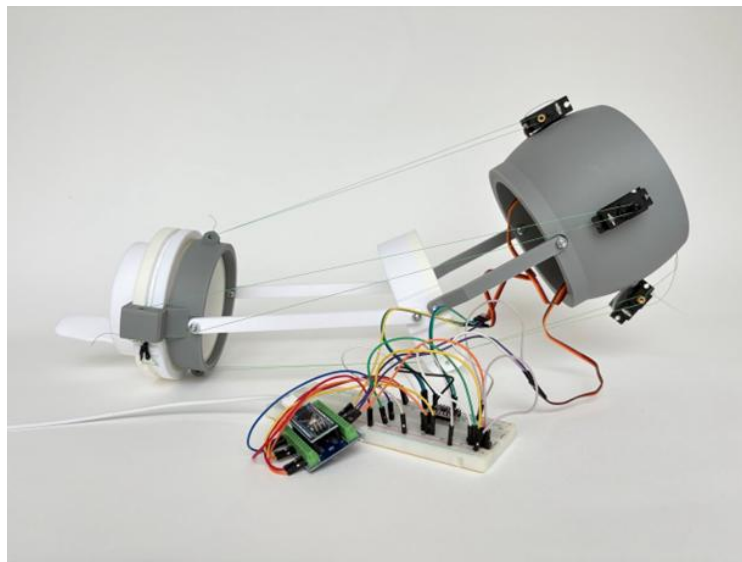


Figure 2 – 3D printed physical prototype of the exoskeleton with Arduino-based control system (1 DOF – PS motion)

The results of simulation modeling are described in [16], while the control algorithm and electronic architecture of the device are detailed in [17].

#### *Pronation-Supination Motion of the Elbow Joint and Mathematical Modeling*

The elbow joint is a complex articular system within the human upper limb. It enables rotational motion between the forearm and the upper arm, facilitating key functional movements such as pronation (inward rotation) and supination (outward rotation). These movements are not

confined solely to the wrist but are primarily executed at the elbow joint through the rotation of the radius bone around the ulna. Therefore, accurate control of this motion using a rehabilitation device requires dedicated mechanical and mathematical modeling.

In this project, a simplified 1-degree-of-freedom (1 DOF) dynamic model was developed to simulate the rotational movement at the elbow. The model considers the mass involved in the motion, the moment of inertia, and the influence of gravity, and is based on the Lagrangian formulation (Figure 3).

The Lagrangian function  $L$  is defined as the difference between the kinetic energy  $T$  and the potential energy  $V$ :

$$L = T - V \quad (1)$$

The kinetic energy is expressed as:

$$T_{ps} = \frac{1}{2} J_{PS} \dot{\theta}_{PS}^2 \quad (2)$$

The potential energy is:

$$V_{PS} = -mg \times \frac{W}{2} \sin \theta_{PS} \quad (3)$$

Where:

- $J_{PS}$  - is the rotational moment of inertia,
- $m$  - is the mass between the elbow and forearm,
- $W$  - is the distance from the axis of rotation to the center of mass,
- $\theta_{PS}$  - is the pronation/supination angle.

Thus, the full Lagrangian becomes:

$$L = \frac{1}{2} J_{PS} \dot{\theta}_{ps}^2 + mg \times \frac{W}{2} \sin \theta_{PS} \quad (4)$$

The Euler–Lagrange equation is written as:

$$\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\theta}_{PS}} \right) - \frac{\partial L}{\partial \theta_{PS}} = T - b\dot{\theta}_{PS} \quad (5)$$

Expanding this leads to:

$$J_{PS} \dot{\theta}_{PS} - mg \times \frac{W}{2} \cos \theta_{PS} = T - b\dot{\theta}_{PS} \quad (6)$$

Finally, solving for angular acceleration:

$$\ddot{\theta}_{PS} = \frac{1}{J_{PS}} \left[ T - b\dot{\theta}_{PS} + mg \times \frac{W}{2} \cos \theta_{PS} \right] \quad (7)$$

This model enables precise control of the pronation–supination motion at the elbow joint in an exoskeleton device. It provides a foundational basis for further development of control algorithms, sensor feedback systems, and motor torque calculations.

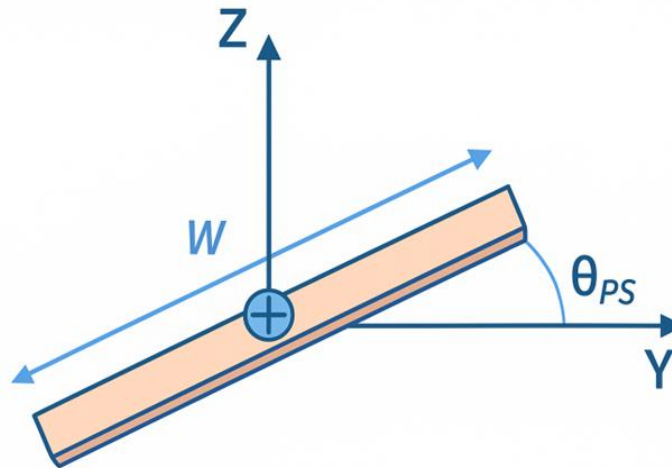


Figure 3 – Simplified dynamic model of pronation–supination movement at the elbow joint

#### *Model assumptions and parameter identification*

In the proposed dynamic model, the pronation–supination motion of the forearm is represented as a single rotational degree of freedom about a fixed axis. The model parameters were selected based on standard anthropometric assumptions commonly used in preliminary biomechanical analyses. The forearm segment was approximated as a rigid body with uniformly distributed mass. The mass and geometric dimensions of the forearm were estimated using average anthropometric data reported in biomechanics literature.

The moment of inertia was calculated assuming a homogeneous cylindrical segment rotating about its longitudinal axis. This simplified representation allows capturing the dominant inertial effects while maintaining analytical tractability of the model. Viscous damping and muscle-generated torques were not explicitly included at this stage, as the objective of the model is to support mechanical design decisions and initial control strategy development rather than patient-specific biomechanical prediction. The adopted assumptions and corresponding parameters are summarized in Table 2.

Table 2 – Model parameters and assumptions

Parameter	Symbol	Value	Unit	Source / Assumption
Forearm mass	$m$	1.1–1.3	kg	Average anthropometric data
Distance to center of mass	$l$	0.14–0.16	m	Forearm length proportion
Moment of inertia	$J$	0.016–0.020	kg·m <sup>2</sup>	Uniform rigid segment assumption
Pronation/supination angle	$\theta$	±40	deg	Experimental range
Viscous damping coefficient	$b$	neglected	–	Simplified preliminary model

It should be emphasized that the proposed dynamic model is intended as a design-oriented and control-support tool rather than a subject-specific biomechanical predictor. The primary objective of the model is to estimate the required actuation torque, justify the selected motion profile, and support the development of the initial control strategy for the exoskeleton.

Therefore, the model deliberately adopts a simplified representation of the pronation–supination motion and does not include muscle activation dynamics, joint compliance, or subject-dependent biomechanical variability. Such effects are expected to influence the system behavior under real rehabilitation conditions and will be addressed in future studies involving load application and human–robot interaction experiments. Within the scope of this work, the simplified model provides sufficient accuracy for preliminary mechanical design and experimental validation of the prototype.

Although the proposed dynamic model was not intended for precise numerical prediction, it provides qualitative insight into the expected motion characteristics of the system. Under sinusoidal command inputs, the model predicts smooth periodic angular trajectories dominated by a single rotational axis.

The experimentally measured pronation–supination motion exhibits a similar sinusoidal profile, as shown in Fig. 8, with stable amplitude and repeatable cycles. The achieved angular range of approximately 38–40° is consistent with the predefined motion profile used in both modeling assumptions and experimental testing. This qualitative agreement confirms that the simplified dynamic model adequately captures the dominant kinematic behavior of the prototype and is suitable for preliminary design validation and control development.

The physical prototype of the exoskeleton was tested under laboratory conditions to evaluate its capability to perform pronation/supination motion at the elbow joint (Figure 4). The rotational movement was actuated using a servo motor, and the motion was transmitted to the elbow's rotational module via a cable-driven system. To assess the angular accuracy and repeatability of the motion, an Inertial Measurement Unit (IMU) sensor was employed. This sensor continuously recorded angular changes in real-time during the motion.



Figure 4 – Experimental setup for controlling pronation/supination movement at the elbow joint: prototype equipped with servo motor, cable driver, and IMU sensor

*The device was evaluated through the following steps:*

- Predefined angular commands were sent to the servo motor;
- The actual angles achieved were measured via the IMU sensor for each command;
- System response time, angular deviation, and repeatability were analyzed.

Initial results demonstrated that the prototype could accurately reproduce commanded motions. Motion trajectories recorded by the IMU were compared to the input commands, revealing an average angular deviation within  $\pm 3$  degrees, which is considered acceptable for rehabilitation applications.

During operation, the system remained stable, showing no signs of mechanical vibration or disturbance. The modular construction allowed easy adjustment to fit different users' arms, making the system convenient to configure and reassemble.



Figure 5 – Screenshots from the experimental test demonstrating device movement

Figure 6 presents a graph of the linear acceleration recorded by the IMU sensor during the movement of the elbow exoskeleton. Data from the three axes (X, Y, Z) describe the dynamics of motion over time:

- The  $a_x$  and  $a_y$  components exhibit sinusoidal patterns, indicating the repetitive nature of the rotational motion;
- The  $a_z$  component remains relatively constant, suggesting that the Z-axis of the sensor aligns with the gravitational vector and that motion occurs primarily in the horizontal plane.

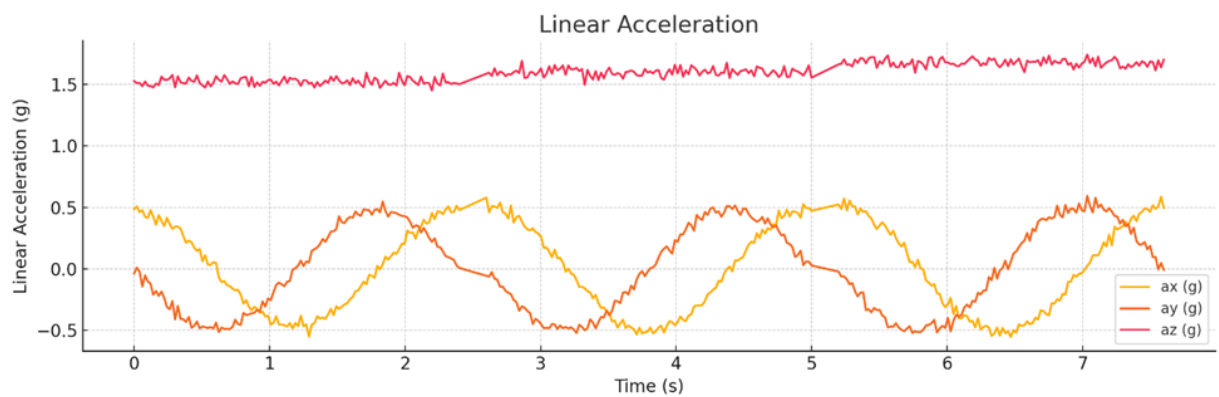


Figure 6 – Linear acceleration graph from IMU sensor (X, Y, Z axes)

Figure 7 shows the angular velocity recorded during the pronation/supination movement. Gyroscope data represent motion intensity along the three axes:

- $g_x$  displays a strong oscillatory pattern around  $\pm 45$  deg/s, indicating it as the primary rotational axis;
- $g_y$  and  $g_z$  show relatively minor fluctuations, confirming that the motion is predominantly confined to a single axis.

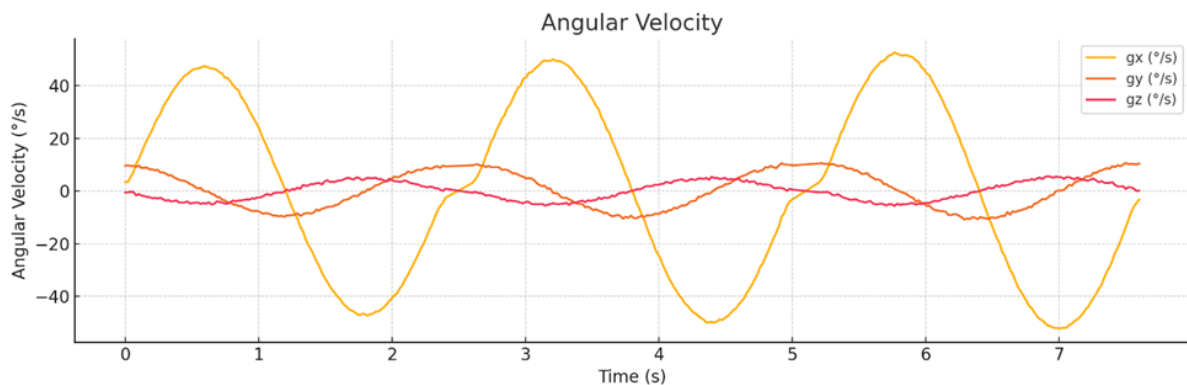


Figure 7 – Angular velocity graph ( $g_x$ ,  $g_y$ ,  $g_z$ ) from IMU sensor

Figure 8 illustrates the angular displacement over time obtained by integrating the gyroscopic data along the X-axis, corresponding to the pronation/supination motion:

- The curve has a sinusoidal shape, representing cyclic oscillations;
- The peak angular displacement reaches approximately 38-40 degrees, returning to 0 degrees during rest phases;
- Three full motion cycles are observed (0–2.5 s, 2.5–5.0 s, 5.0–7.5 s), indicating stable and repeatable system behavior.

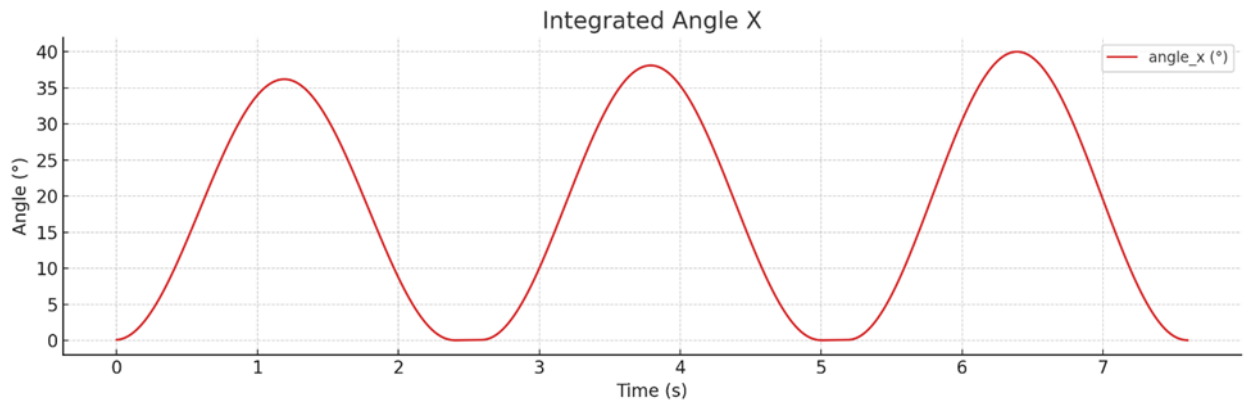


Figure 8 – Time-integrated angular displacement (X-axis, pronation/supination motion).

These findings demonstrate that the exoskeleton prototype is functional and suitable for modeling and controlling pronation/supination motion of the elbow joint. The recorded data can serve as a foundation for further system optimization, control algorithm refinement, and adaptation for therapeutic rehabilitation exercises.

#### Discussion of Results.

The experimental results demonstrate that the developed elbow exoskeleton prototype is capable of generating stable and repeatable pronation–supination motion under controlled laboratory conditions. The recorded angular trajectories show a clear sinusoidal profile with consistent amplitude across multiple cycles, indicating reliable mechanical behavior and proper alignment of the rotational axis.

The average angular deviation between the commanded and measured trajectories remained within  $\pm 3^\circ$ , which can be considered acceptable for early-stage rehabilitation devices, where smoothness and repeatability of motion are often prioritized over high-precision positioning. The calculated RMSE and maximum angular error values further confirm that the control system is able to track predefined motion profiles with sufficient accuracy for preliminary rehabilitation exercises.

The absence of noticeable sensor drift during consecutive motion cycles suggests that the IMU-based measurement system provides stable angular feedback over the duration of the experiment. Minor phase delays observed between the reference and measured signals are attributed to servo motor response characteristics and compliance of the cable-driven transmission. These effects are common in lightweight wearable mechanisms and did not significantly affect the overall motion pattern.

It should be noted that the experiments were conducted in free space, without external load and without direct interaction with the human limb. As a result, biomechanical factors such as muscle resistance, joint compliance, and subject-dependent variability were not considered in the present study. This limitation was intentionally accepted to ensure safe and controlled validation of the mechanical structure and control architecture at an early development stage.

Despite these limitations, the obtained results confirm that the proposed prototype provides a solid experimental foundation for further development. Future work will focus on extending the system to multiple degrees of freedom, incorporating load conditions, and conducting human–

robot interaction experiments under ethical approval and clinical supervision. These steps will allow a more comprehensive assessment of the device's rehabilitation potential.

Table 3 – Summary and interpretation of experimental results

Aspect	Observed result	Interpretation / significance
Motion trajectory shape	Sinusoidal, smooth	Confirms correct kinematic behavior and stable actuation
Angular range	~38–40°	Sufficient for basic pronation–supination rehabilitation tasks
Average angular deviation	$\leq \pm 3^\circ$	Acceptable accuracy for early-stage rehabilitation devices
RMSE	Low, stable across cycles	Indicates reliable tracking performance
Maximum angular error	Within predefined tolerance	No critical positioning errors detected
Repeatability	High cycle-to-cycle consistency	Confirms mechanical robustness and control stability
Phase delay	Small, constant	Caused by actuator and cable dynamics; acceptable at this stage
Sensor drift	Not observed	IMU feedback suitable for short-term rehabilitation exercises
Test conditions	Free space, no load	Safe preliminary validation; biomechanical effects excluded

### Conclusion.

This paper presented the structure, mathematical model, CAD design, and physical prototype of an exoskeleton aimed at restoring pronation/supination movement of the elbow joint. A SolidWorks-based model with two degrees of freedom (flexion/extension and pronation/supination) was developed; however, the physical prototype implemented only one DOF – pronation/supination motion. During testing, the accuracy and stability of the movement execution were evaluated using a servo motor and an IMU sensor.

The experimental results demonstrated that the device is capable of accurately reproducing the commanded motion and reliably tracking angular trajectories. The average angular deviation remained within  $\pm 3^\circ$ , which is considered sufficiently accurate for early-stage rehabilitation applications. The observed repeatability of motion and stable system behavior confirm the feasibility of the proposed mechanical and control architecture. In addition, the modular design allows the device to be adapted to different users and provides flexibility for integrating an additional degree of freedom in future iterations.

The outcomes of this study highlight effective engineering approaches for the design and experimental validation of rehabilitation exoskeletons and provide a solid foundation for further development. Future work will focus on extending the prototype to a full two-degree-of-freedom system, incorporating external load conditions, and refining the control algorithms to account for actuator dynamics and transmission compliance. Furthermore, human–robot interaction experiments will be conducted under appropriate ethical approval and medical supervision to evaluate biomechanical compatibility, safety, and rehabilitation effectiveness. These steps will enable a comprehensive assessment of the proposed device in clinically relevant scenarios.

### Acknowledgement

*This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan within the framework of the program AP27508009.*

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## ШЫНТАҚ ЭКЗОСКЕЛЕТІ ПРОНАЦИЯ-СУПИНАЦИЯ ҚОЗГАЛЫСЫНА АРНАЛҒАН: МОДЕЛЬДЕУ ЖӘНЕ ПРОТОТИПТИ СЫНАУ

*Аңдатпа.* Бұл мақалада шынтақ буынының пронация/супинация қозғалысын оңалту мақсатында қолдануға арналған экзоскелет құрылғысының жобалануы мен тәжірибелік сынағы сипатталады. Аталған қозғалысты дәл және қауіпсіз түрде жүзеге асыру оңалту экзоскелеттеріндегі негізгі техникалық қиындықтардың бірі болып табылады, себебі бұл қозғалыс күрделі биомеханикалық өзара әрекеттесулер мен білектегі сүйектердің айналуына байланысты. Жоба аясында SolidWorks бағдарламасында екі еркіндік дәрежесі (DOF) бар CAD үлгісі жасалды. Кейіннен физикалық прототип құрастырылып, зертханалық жағдайда бір еркіндік дәрежесі – пронация/супинация қозғалысына сынақ жүргізілді. Қозғалыс дәлдігі IMU сенсоры арқылы тіркеліп, басқару тиімділігі бағаланды.

Ұсынылған құрылғы инсульттан кейінгі нейромоторлық функцияларды қалпына келтіру, шынтақ буынының контрактурасын түзету және неврологиялық аурулары бар пациенттерді оңалту үдерісінде қолдануға арналған. Эксперимент нәтижелері құрылғының оңалтуға жарамды екенін көрсетті.

**Түйін сөздер:** шынтақ экзоскелеті, пронация-супинация, оңалту робототехникасы, CAD модель, IMU сенсоры, 2 DOF экзоскелет.

## ЭКЗОСКЕЛЕТ ДЛЯ ДВИЖЕНИЯ ПРОНАЦИЯ-СУПИНАЦИЯ ЛОКТЕВОГО СУСТАВА: МОДЕЛИРОВАНИЕ И ЭКСПЕРИМЕНТАЛЬНОЕ ИСПЫТАНИЕ

*Аннотация.* В данной статье представлено проектирование и экспериментальная оценка экзоскелетного устройства, предназначенного для реабилитации движения пронации/супинации локтевого сустава. Точное и безопасное выполнение данного типа движения остается одной из основных технических задач в реабилитационных экзоскелетах, поскольку оно связано со сложными биомеханическими взаимодействиями и вращением костей предплечья. В рамках проекта была разработана CAD-модель с двумя степенями свободы (DOF) в среде SolidWorks. Затем был изготовлен физический прототип и проведены лабораторные испытания одной степени свободы – движения пронация/супинация. Точность выполнения движения фиксировалась с помощью IMU-сенсора, а также оценивалась эффективность системы управления.

Предлагаемое устройство предназначено для использования в процессе реабилитации пациентов с неврологическими нарушениями, включая восстановление нейромоторных функций после инсульта и коррекцию контрактур локтевого сустава. Экспериментальные результаты подтверждают пригодность устройства для реабилитационных целей.

**Ключевые слова:** экзоскелет локтевого сустава, пронация-супинация, реабилитационная робототехника, CAD-модель, IMU сенсор, экзоскелет с 2 степенями свободы.

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