

Article

Modular BLDC Actuator Design for Upper-Extremity Rehabilitation Devices

Bünyamin Ergezgin *  and Alper Kadir Tanyıldızı 

Department of Mechatronics Engineering, Faculty of Engineering, Fırat University, 23119 Elazığ, Türkiye; atanyildizi@firat.edu.tr

* Correspondence: bergezgin@firat.edu.tr

Abstract

Upper-extremity rehabilitation devices require compact actuators capable of slow, controllable motion. This study presents a modular actuator integrating a brushless direct-current motor, a custom 7.2:1 planetary gearbox, a motor-shaft incremental encoder, a commercial RC-type electronic speed controller, and an external triac-based phase reconfiguration circuit. The switching circuit is an implementation element that separates drive-command magnitude from direction selection; it is not presented as a novel drive topology, and its electrical behaviour was not characterised. The mechanical components were manufactured by fused-deposition modeling using polylactic acid for low-cost rapid prototyping. Encoder feedback was converted through the gearbox ratio to estimate the output angle response. The actuator was tested with suspended masses of 250 g, 500 g, and 1 kg on a 25 cm moment arm, corresponding to nominal maximum gravitational torques of approximately 0.61, 1.23, and 2.45 Nm in the horizontal arm configuration. A sinusoidal reference of 90° amplitude at 0.5 Hz was tracked in all three recorded tests. The root-mean-square tracking error increased monotonically with load, from 12.4° to 13.3° and 15.0°, and the phase lag increased from 53 ms to 58 ms and 66 ms, indicating a systematic load-dependent degradation under a single fixed gain set. A load capacity assessment of the printed transmission indicates that surface durability, rather than tooth bending, governs the usable torque range. The results demonstrate proof-of-concept closed-loop and bidirectional bench operation. Direct output-shaft sensing and repeated trial validation remain necessary before rehabilitation device integration.

Keywords: brushless DC motor; modular actuator; planetary gearbox; PID position control; rehabilitation robotics; three-dimensional printing



Academic Editors: Zhuming Bi,
Monica Tiboni, Monica Malvezzi and
Maria Cristina Valigi

Received: 22 July 2026

Revised: 23 August 2026

Accepted: 8 September 2026

Published: 14 September 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Upper-extremity motor impairments caused by stroke, trauma, neuromuscular disorders, or age-related functional losses can significantly reduce an individual's ability to perform activities of daily living independently. Conventional rehabilitation generally depends on repetitive therapist-assisted exercises, which may increase clinical workload and limit the consistency of treatment sessions. Robotic rehabilitation systems provide an alternative approach by enabling controlled, repeatable, and measurable therapeutic movements for upper-limb recovery.

In these systems, the actuator is a key design element because it directly affects the size, weight, torque capacity, motion accuracy, safety, and usability of the rehabilitation

device. Pneumatic and hydraulic actuators can generate high output forces, but they generally require auxiliary units and increase system complexity. Cable-driven and compliant mechanisms can reduce distal mass and improve user comfort; however, they may introduce routing difficulties, backlash, nonlinear transmission behaviour, or reduced stiffness. Electric motor-based solutions are therefore widely preferred due to their compactness, controllability, and ease of integration with electronic control units.

Brushless direct-current motors are particularly attractive for robotic and biomedical actuation because of their high efficiency, high power density, fast response, and low maintenance requirements. However, their high rotational speed is not directly suitable for upper-extremity rehabilitation, in which the required output motion is slow, smooth, and repeatable. Therefore, the motor output must be adapted through a transmission mechanism that primarily reduces speed and, as a result, increases the available output torque. This requirement becomes more important when the actuator must be integrated into a compact rehabilitation device without increasing the mechanical volume.

Another design challenge is integration of the actuator subsystems. In many robotic rehabilitation systems, the motor, reducer, feedback sensor, driver, and direction-control unit are selected as separate components. Such an arrangement may complicate mechanical assembly, increase wiring and packaging requirements, and reduce modularity. For practical upper-extremity rehabilitation applications, an actuator package should combine speed reduction, torque transmission, position feedback, drive electronics, and bidirectional motion capability within a compact and reproducible architecture.

Based on these requirements, this article focuses on the development and experimental evaluation of a modular brushless direct-current actuator package for upper-extremity rehabilitation devices. The proposed actuator combines a brushless direct-current motor, a custom planetary gearbox, encoder-based feedback, a commercial RC-type electronic speed controller, and an external triac-based phase reconfiguration circuit. The selected controller supports reverse operation; however, during preliminary operation, its native forward–stop–reverse logic introduced a comparatively long waiting interval between opposite commands. The external circuit was therefore used to select the motor rotation direction independent of the drive-command magnitude, while the planetary gearbox converted the high motor speed into a lower output speed range. The emphasis of the present evaluation is on the mechanical and position-control behaviour of the resulting package; the electrical behaviour of the switching arrangement is outside the scope of this study.

The remainder of this article is organised as follows. Section 2 presents related work on upper-extremity rehabilitation robots and actuation technologies. Section 3 summarises the contribution and novelty of the proposed actuator architecture. Section 4 describes the system design, mechanical transmission, electronic drive structure, encoder integration, control strategy, and experimental setup. Section 5 presents the experimental results and discusses the load-dependent position tracking performance. Finally, Section 6 concludes the article and outlines future research directions.

2. Related Work

Robotic rehabilitation systems have been widely investigated to support repetitive, task-oriented, and measurable therapeutic exercises for patients with upper-limb impairments. Early upper-extremity rehabilitation devices focused mainly on assisting shoulder, elbow, wrist, or hand movements through different mechanical architectures and control approaches. T-WREX was developed to automate arm movement training after stroke by providing gravity-reduced functional exercises with quantitative feedback [1]. WREX was later adapted with series elastic actuation to provide powered assistance in an upper-limb

exoskeleton structure [2]. The Maryland-Georgetown-Army exoskeleton introduced a multi-degree-of-freedom shoulder rehabilitation architecture that included scapular motion and allowed the evaluation of force, range of motion, and functional task performance [3]. RUPERT used pneumatic muscles to provide repetitive upper-extremity therapy [4], while L-EXOS was developed as a robotic exoskeleton for upper-limb rehabilitation in virtual reality environments [5]. These systems demonstrate the importance of robotic assistance in rehabilitation; however, they also show that actuator selection and integration remain critical design challenges.

Recent studies have further emphasized portability, modularity, and compact actuation in upper-limb assistive and rehabilitation systems. UP-CARE was proposed as a portable cable-assisted elbow exoskeleton using a brushless direct-current motor, a custom 3D-printed two-stage planetary gearbox, and a dual-pulley cable transmission [6]. This system demonstrated that the combination of lightweight additive-manufactured transmission components and electric actuation can improve portability while providing the torque required for elbow assistance. Similarly, a hybrid soft-rigid elbow exosuit was recently developed by combining compact electric actuation, planetary reduction, tendon-driven transmission, embedded sensing, and a generic interaction controller [7]. These recent examples indicate that modern upper-extremity assistive devices increasingly rely on integrated mechatronic actuation modules rather than isolated motor units.

Different actuation technologies have been employed in rehabilitation and assistive robotic systems. Pneumatic actuators and artificial muscles provide compliant interaction and relatively high force-to-weight ratios, but they usually require external air supply units and may suffer from nonlinear behaviour, response delay, and reduced position-control accuracy. Hydraulic actuators can generate high forces and torques, yet they increase system weight, require additional power units, and may not be suitable for compact wearable rehabilitation devices. Cable-driven mechanisms reduce distal mass and can improve comfort, but they introduce routing complexity, cable tension management requirements, and possible backlash or compliance-related tracking errors. Series elastic, compliant, and variable-stiffness actuator structures can improve safety and adaptability in physical human–robot interaction; however, they often require more complex mechanical design, parameter optimization, and control strategies [8].

Electric motor-based solutions are attractive for rehabilitation robots because they offer clean operation, compactness, controllability, and easier integration with electronic control units. Brushed direct-current motors have simple drive requirements, but their brushes and commutators cause wear, maintenance needs, and electromagnetic noise. Stepper motors are useful for open-loop position control, yet their torque decreases at higher speeds and their motion can become vibratory under certain operating conditions. Brushless direct-current motors overcome several of these limitations by providing high efficiency, high power density, low maintenance, and fast dynamic response. In addition, brushless direct-current motor modeling and simulation studies show that these motors are suitable for precision speed control applications [9]. For these reasons, brushless direct-current motors are frequently preferred in robotic actuation systems requiring compact and efficient motion generation.

Despite these advantages, brushless direct-current motors generally operate at relatively high speeds, whereas upper-extremity rehabilitation requires slow, repeatable, and controlled joint movements. Therefore, a speed reduction mechanism is needed to adapt the motor output to the rehabilitation movement range. Planetary gearboxes are suitable for this purpose because they provide coaxial input–output alignment, compact size, and high torque transmission capability. However, the actuator should not be considered only as a motor and gearbox combination. For practical rehabilitation applications, position

feedback, drive electronics, direction control, mechanical interfaces, and compact packaging must also be considered together.

Although recent upper-limb exoskeletons and exosuits demonstrate the effectiveness of integrated actuation and transmission systems, many rehabilitation devices still rely on actuator solutions that are either bulky, application-specific, or dependent on external drive arrangements. In this context, there is a need for a compact actuator package that reduces the high speed of a brushless direct-current motor to a rehabilitation-compatible output speed, provides sufficient torque transmission, integrates encoder-based feedback, and supports frequently alternating bidirectional motion without depending on a conventional RC controller's internal reverse-entry sequence. The actuator architecture proposed in this study addresses this need by combining a brushless direct-current motor, a custom planetary gearbox, an encoder, a commercial electronic speed controller, and an external triac-based phase reconfiguration circuit in a modular structure for upper-extremity rehabilitation devices.

3. Contribution and Novelty

This study presents a modular brushless direct-current actuator package intended for upper-extremity rehabilitation research. The proposed system integrates a brushless direct-current motor, a custom-designed planetary gearbox, a configurable incremental encoder, a commercial RC-type electronic speed controller, and an external triac-based phase reconfiguration circuit. The planetary gearbox is designed primarily to reduce the high motor speed to a lower movement range while increasing the available output torque. Motor-shaft encoder feedback is converted through the gearbox ratio to evaluate the estimated position response under different suspended mass conditions. The external circuit is not used to add reverse capability to a unidirectional controller, and it is not claimed as a novel power electronic topology; phase interchange for direction reversal is a long-established technique. It is included as the implementation element that allowed direction to be selected independently of drive-command magnitude in this prototype. The actuator prototype and the initial experimental framework were developed within the scope of the first author's M.S. thesis, and this article extends that work by reorganising the system architecture, updating the related literature, and providing a journal-oriented analysis of the load-dependent position tracking and switching behaviour [10].

It should be noted that integrated brushless direct-current actuator modules that combine a planetary reducer, encoders, and a compact drive are already commercially mature and have been adopted in advanced robotic systems, such as the proprioceptive quasi-direct-drive joint actuators developed for the MIT Cheetah [11] and the open-source, low-cost quasi-direct-drive actuators of platforms such as Stanford Doggo [12]. The selected HobbyKing X-Car 120 A electronic speed controller is commercially specified for forward-only or forward-with-reverse operating modes [13]. In the prototype, however, its native reversal sequence required a stop/neutral transition and produced a comparatively long waiting interval during alternating position commands. Dedicated servo drives such as ODrive use cascaded position, velocity, and current-control loops and accept direct position, velocity, and torque commands [14]. The objective of the present work was not to replicate such an advanced servo drive or to surpass integrated actuators in power density, but to retain a low-cost commercial controller as the power and commutation stage and add an external phase reconfiguration circuit. The contribution therefore lies in the accessible system-level integration of an off-the-shelf brushless motor, a 3D-printed planetary gearbox, motor-side encoder feedback and an RC-type electronic speed controller, together with two experimental outcomes: an identification of the mechanism that limits the load capacity of the additively manufactured transmission, and a quantification of how single-gain-set

tracking performance degrades as the gravitational load is increased. This architecture is intended for low-budget rehabilitation research, rapid prototyping, and educational settings, while the switching circuit remains a proof-of-concept arrangement rather than a safety-rated bidirectional servo drive.

The main contributions of this study can be summarised as follows:

- An accessible, low-cost modular actuator architecture is developed for upper-extremity rehabilitation research by integrating an off-the-shelf brushless motor, an additively manufactured planetary gearbox, motor-shaft encoder feedback, a commercial RC-type electronic speed controller, and an external phase reconfiguration circuit that separates direction selection from drive-command magnitude.
- A custom planetary gearbox with a 7.2:1 reduction ratio is designed and manufactured to reduce output speed and increase usable torque in a compact mechanical configuration.
- A load capacity assessment of the additively manufactured planetary stage is carried out, showing that tooth-root bending stress remains far below the strength of the printed material, while the Hertzian contact stress approaches the range accepted for continuous operation of polymer gears; surface durability is therefore identified as the governing constraint on the usable torque range.
- The actuator prototype is experimentally evaluated under three suspended mass conditions corresponding to nominal maximum gravitational torque levels of approximately 0.61 Nm, 1.23 Nm, and 2.45 Nm at the horizontal arm configuration.
- The experimental results are compared in terms of peak excursion, rise time, root-mean-square tracking error, amplitude ratio, and phase lag, and a monotonic load-dependent degradation of tracking performance under a single fixed gain set is reported.

4. System Design and Methodology

This section describes the design requirements, actuator architecture, mechanical transmission structure, electronic drive unit, encoder integration, control strategy, and experimental setup of the proposed modular brushless direct-current actuator. The design methodology was established according to the main requirements of upper-extremity rehabilitation devices, including low output speed, sufficient torque transmission, compactness, position feedback, frequently alternating bidirectional motion, and ease of mechanical integration.

4.1. Design Requirements

The actuator was designed for use in upper-extremity rehabilitation devices where the output motion must be slow, repeatable, and controllable. Since rehabilitation exercises require controlled joint movements rather than high-speed rotation, the primary mechanical requirement was to reduce the high rotational speed of the brushless direct-current motor to a suitable output speed range. At the same time, the reduction mechanism was expected to increase the usable output torque without significantly increasing the overall volume of the actuator package.

The main design requirements were defined as follows:

- Reducing the high motor speed to a rehabilitation-compatible output speed;
- Providing sufficient output torque for upper-extremity motion assistance;
- Maintaining a compact and modular mechanical structure;
- Integrating position feedback for closed-loop control;
- Reducing the waiting interval associated with the selected controller's native reverse-entry sequence without replacing the commercial power stage;

- Supporting low-cost prototyping and easy manufacturing;
- Allowing practical integration into future rehabilitation robot joints.

To complement these qualitative requirements with measurable design indicators, the principal specifications of the realised actuator are summarised in Table 1. The selected motor has a mass of 630 g. In the prototype, the motor was supplied at 12 V, giving a theoretical no-load carrier speed of approximately 175 rpm after the 7.2:1 single-stage planetary reduction. The commanded rehabilitation motion was considerably slower because it was governed by the outer position-control loop. The prototype was tested against suspended masses that generated a nominal maximum gravitational load torque of up to 2.45 Nm at the horizontal arm configuration.

Table 1. Principal quantitative specifications of the proposed modular actuator.

Parameter	Value
Motor	Eagle Power EA90, KV105
Speed constant	105 rpm/V
Motor dimensions	Ø88.5 mm × 46 mm
Motor mass	630 g
Supply voltage (prototype)	12 V
Transmission	Single-stage planetary (FDM, PLA)
Gear teeth (sun/planet/ring)	15/39/93
Reference trajectory	90° amplitude sinusoid at 0.5 Hz
Controller sample interval	10 ms (100 Hz)
Pitch diameter (sun/planet/ring)	16.9/43.9/104.6 mm
Module/pressure angle/face width	1.125 mm/14.5°/12 mm
Reduction ratio	7.2:1
Theoretical no-load output speed	≈175 rpm
Maximum nominal gravitational test torque	Up to 2.45 Nm (horizontal arm)
Moment arm	25 cm
Motor-side position feedback	AMT102-V incremental encoder
Controller	PID ($K_p = 1.1$, $K_i = 0.001$, $K_d = 0.05$)

4.2. Overall Actuator Architecture

The proposed actuator package consists of five main subsystems: a brushless direct-current motor, a custom planetary gearbox, a commercial RC-type electronic speed controller, an external triac-based phase reconfiguration circuit, and an encoder-based feedback unit.

The brushless direct-current motor provides the primary mechanical power. The planetary gearbox reduces the motor speed and transmits torque to the carrier output shaft. The electronic speed controller provides the three-phase power and commutation stage, while the external phase reconfiguration circuit is placed between the controller and the motor to change the selected phase-connection path. Consequently, the drive-command magnitude and motor rotation direction are handled separately. The incremental encoder measures the motor-shaft position. This measurement is divided by the gearbox ratio to obtain an estimated output angle signal for the outer position-control loop. Because the encoder is located upstream of the gearbox, this estimate does not directly capture gearbox backlash, torsional deformation, or load-dependent transmission error. A general representation of the proposed actuator structure is shown in Figure 1. The package provides a single rotational degree of freedom: the planet carrier is the only output member, and it rotates about the motor axis. The module is therefore intended to realise one powered joint, and a multi-joint rehabilitation structure would be obtained by combining several such modules.

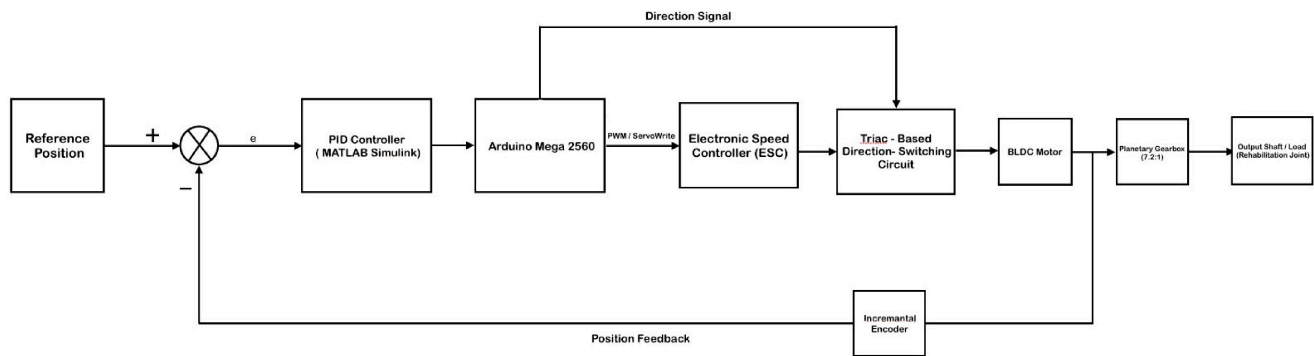


Figure 1. Proposed modular BLDC actuator architecture.

This integrated structure allows the actuator to be evaluated not only as a motor-reducer pair but also as a complete modular actuation package, including mechanical transmission, electronic switching, and feedback control.

4.3. BLDC Motor and Electronic Drive Unit

An Eagle Power EA90 KV105 brushless direct-current motor was selected as the main drive unit because of its compact structure and suitability for robotic actuation. The motor has a diameter of 88.5 mm, a length of 46 mm, and a mass of 630 g. During the reported experiments, the motor was supplied at 12 V, and the electrical input power and motor phase current were not measured. The manufacturer additionally states a catalogue maximum continuous power for this motor; that figure applies to the motor alone under conditions of supply voltage, current, cooling and duty that were not reproduced here; it is unrelated to the mechanical output of the actuator package, and it is therefore not used anywhere in this article.

The motor was driven using a HobbyKing X-Car Beast Series 1:8 Scale 120 A electronic speed controller (Figure 2). The controller was selected as a low-cost, commercially available three-phase power and commutation stage for the sensorless brushless direct-current motor, thereby avoiding the need to design a custom three-phase inverter. The manufacturer's product information specifies forward-only and forward-with-reverse operating modes [13]. During preliminary operation in the present actuator, however, the controller's native reverse-entry sequence required the command to pass through a stopping or neutral stage, producing a comparatively long waiting interval between opposite motion commands. This behaviour is appropriate for RC vehicle drivetrains but interrupted the periodically alternating position reference used in the actuator tests. Dedicated servo drives such as ODrive provide cascaded position, velocity, and current-control loops and accept direct position, velocity, and torque commands [14]. Such a drive would provide more direct bidirectional servo operation, but it represents a more advanced current-sensing architecture than the low-cost controller used here. The objective of the present study was therefore to retain the selected electronic speed controller as the power and commutation stage and add an external phase reconfiguration circuit for direction selection. The ServoWrite command sets the magnitude of the drive effort, while the sign of the position error selects the external switching state. The outer PID loop governs the gear-ratio-converted position estimate calculated from motor-shaft encoder feedback. A limitation is that motor torque and phase current are not commanded or measured directly.

This arrangement retains the commercial electronic speed controller for power conversion and commutation while delegating direction selection to the external phase reconfiguration circuit.



Figure 2. BLDC motor and electronic speed controller used in the actuator prototype.

4.4. Direction-Switching Circuit

The selected electronic speed controller was already capable of reverse operation; therefore, the proposed circuit was not developed to add reverse capability to an otherwise unidirectional controller. Its purpose was to reduce dependence on the controller's firmware-defined forward–stop–reverse sequence, which required a stopping or neutral transition and introduced an undesirable dead time during frequently alternating commands. The circuit was positioned between the electronic speed controller and the brushless direct-current motor and used optically isolated triac-based switching elements to reconfigure the motor phase-connection path (Figure 3). The Arduino sent digital logic signals to the optocoupler inputs, and the optocoupler outputs triggered the triac gates. By interchanging the relevant phase connections, the motor rotation direction was selected independently of the drive-command magnitude.

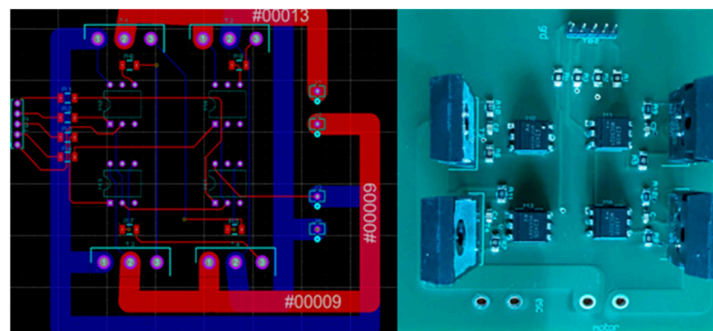


Figure 3. Triac-based phase reconfiguration circuit and manufactured printed circuit board.

The electrical behaviour of the arrangement was not characterised in this study. Motor phase currents, switching transients, and the behaviour of the controller output stage during and after each interchange were not measured. Since triacs remain conducting until the current through them falls below the holding value, the instant at which each switching element actually changes state also cannot be inferred from the logic command alone. It should further be noted that the manufacturer specifies a continuous neutral interval before reverse operation is permitted in the default running mode, introduced to protect the drivetrain of radio-controlled vehicles from torque reversal at speed [15]. The present arrangement does not shorten that interval but bypasses it, because the controller receives forward commands only and its reverse-entry logic is never invoked; the circuit is therefore treated as a proof-of-concept implementation element rather than a characterised drive stage.

For these reasons, the circuit is regarded as a proof-of-concept implementation element rather than a characterised drive stage or a replacement for a safety-rated bidirectional

servo drive. Electrical characterisation of the switching event is identified in Section 5.2 as a required step before the arrangement is used outside bench conditions.

4.5. Planetary Gearbox Design

A custom planetary gearbox was designed to adapt the high-speed output of the brushless direct-current motor to the low-speed motion requirements of upper-extremity rehabilitation. The primary purpose of the gearbox is speed reduction. The increase in output torque is a beneficial consequence of the reduction process. A planetary configuration was selected because it provides coaxial input–output alignment, compact packaging, and distributed load transmission through multiple planet gears [16].

In the proposed gearbox, the three mechanical ports of the planetary stage are arranged to obtain a single fixed reduction path. The ring gear is held stationary by fixing it to the gearbox housing, the sun gear is connected to and driven by the brushless direct-current motor shaft and acts as the input, and the planet carrier serves as the output member that drives the moment arm. For a stationary ring gear with sun gear input and carrier output, the speed reduction ratio of a single planetary stage is given by $i = 1 + Z_r/Z_s$, where Z_s and Z_r are the tooth numbers of the sun and ring gears, respectively. In the proposed design, the sun gear has $Z_s = 15$ teeth, each of the three planet gears has $Z_p = 39$ teeth, and the ring gear has $Z_r = 93$ teeth. These values satisfy the coaxial planetary meshing condition $Z_r = Z_s + 2Z_p$ ($93 = 15 + 2 \times 39$), which ensures correct geometric engagement of the planet gears between the sun and ring gears. Substituting the tooth numbers gives $i = 1 + 93/15 = 7.2$, so the carrier output rotates at $1/7.2$ of the motor speed. This reduces the high motor speed to a rehabilitation-compatible range while increasing the available output torque by approximately the same factor, excluding transmission losses.

The reduction ratio was constrained by manufacturability and packaging rather than selected freely. For a single planetary stage, the ratio increases only if the sun gear is made smaller or the ring gear larger. The sun gear is already at 15 teeth, which is below the theoretical interference limit for the pressure angle used, so it cannot be reduced further without compromising the mesh; the ring gear, at 93 teeth, already gives a pitch diameter of 104.6 mm, which exceeds the 88.5 mm diameter of the motor body. Increasing the ratio would therefore enlarge the package diameter in proportion, while adding a second planetary stage would increase axial length, cumulative backlash, and part count, in conflict with the compactness requirement of Section 4.1. The resulting no-load output speed of approximately 175 rpm at 12 V is well above the slow-motion range required in upper-extremity rehabilitation, so the ratio does not restrict the achievable trajectory; the realised motion is governed by the outer position loop.

The gears were generated with a module of 1.125 mm, a pressure angle of 14.5° , and a common face width of 12 mm, giving pitch diameters of 16.875 mm, 43.875 mm, and 104.625 mm for the sun, planet, and ring gears, respectively. Under the most severe test condition, the carrier torque is 2.45 N·m, which corresponds to 0.34 N·m at the sun gear. The resulting tangential force of 40.3 N is distributed over the three planet meshes; applying a load-sharing factor of 1.2 to account for uneven distribution between planets gives approximately 16 N per mesh.

Evaluating the Lewis equation for the sun gear, which is the most heavily loaded member, with a form factor of 0.237 for 15 teeth at a 14.5° pressure angle gives a tooth-root bending stress of approximately 5 MPa. Reported flexural strengths for fused-deposition-manufactured PLA lie in the range of 40–55 MPa, so bending is not the limiting mechanism. The Hertzian contact stress at the sun–planet mesh, evaluated at the pitch point for an elastic modulus of 2.5 GPa and a Poisson ratio of 0.35, is approximately 20 MPa. This lies within the range generally reported as the practical limit for continuous operation of polymer

gears, in which failure develops progressively through surface wear and thermal softening rather than by tooth fracture. Surface durability is therefore the governing constraint, and the 1 kg limit adopted in the experiments corresponds to this constraint rather than to an arbitrary margin.

Because the gears are produced directly from the CAD profile rather than by a generating process, the undercutting associated with cutter interference does not arise. The 15-tooth sun gear nevertheless lies below the theoretical interference limit for a 14.5° pressure angle, and the backlash inherent to fused-deposition manufacturing is relied upon to accommodate this. A larger pressure angle would increase the tooth-root thickness and reduce both stresses and is recommended for future versions.

The gearbox components were designed in SOLIDWORKS 2023 and manufactured by fused-deposition modeling with polylactic acid (PLA). This approach enabled low-cost and rapid prototyping of the gear components (Figure 4). However, FDM parts generally have lower dimensional accuracy and rougher surfaces than machined or molded gears, which can introduce backlash, friction, and reduced smoothness after assembly [17]. PLA also has limited long-term wear resistance, thermal stability, and mechanical durability under continuous loading. The reported short-duration bench tests demonstrated encoder-derived trajectory tracking, but they did not directly quantify output-shaft backlash, transmission efficiency, wear, or long-term durability. The additively manufactured gearbox should therefore be regarded as a proof-of-concept prototype rather than a transmission suitable for high-precision or long-duration clinical operation. Higher-precision processes, such as stereolithography, selective laser sintering, CNC-machined polymer, or metal gears, together with appropriate post-processing and lubrication, should be considered in future versions.

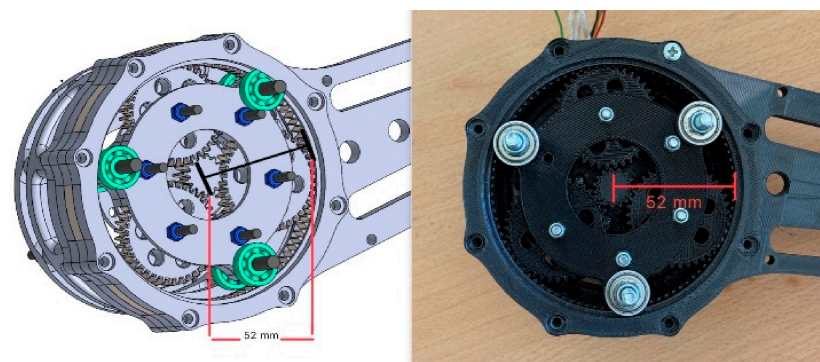


Figure 4. Custom planetary gearbox design and manufactured gearbox assembly.

4.6. Encoder Integration

Position feedback was obtained using an AMT102-V modular, incremental encoder mounted directly on the motor shaft.

A custom 3D-printed adapter was designed to provide mechanical coupling between the motor shaft and the encoder (Figure 5). The encoder measures motor-shaft rotation and therefore provides an upstream measurement relative to the planetary gearbox.

The AMT102-V encoder was configured to 500 pulses per revolution. With quadrature decoding, this corresponds to 2000 counts per motor revolution. Considering the 7.2:1 gearbox ratio, one estimated carrier/output revolution corresponds to 14,400 encoder counts. Therefore, the estimated output angle was calculated as

$$\theta_{\text{est}} = \frac{N}{14400} \times 360^\circ = \frac{N}{40},$$

where N is the accumulated quadrature count.

This estimate was compared with the reference trajectory during the experiments. Because no independent sensor was installed on the carrier or output shaft, the reported position response does not include direct measurement of gearbox backlash, elastic deformation, or other transmission errors.

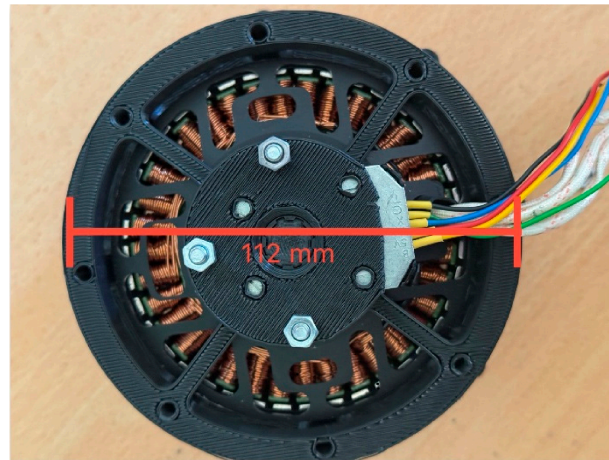


Figure 5. Encoder mounting structure on the actuator prototype.

4.7. Control Strategy

A classical proportional–integral–derivative control structure was used to evaluate the encoder-derived position response. The control signal was generated from the error between the reference angle and the gear-ratio-converted angle estimated from the motor-shaft encoder. The proportional term increases corrective action, the integral term reduces residual error, and the derivative term contributes damping to rapid error variations.

The continuous-time PID control law is expressed as

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt},$$

where $e(t)$ is the estimated position error, and K_p , K_i , and K_d are the proportional, integral, and derivative gains, respectively.

The controller gains were determined empirically through iterative manual tuning on the physical bench setup rather than through an analytical or model-based procedure, because the prototype includes nonlinear electronic speed controller behaviour, gearbox friction and backlash, and a minimum effective drive threshold. Starting from proportional-only action, K_p was increased until an adequate response was obtained; derivative action was then added to reduce overshoot and oscillation, and a small integral gain was introduced to reduce residual error. Maximum overshoot, rise time, and steady-state error of the encoder-derived response were used as tuning criteria. The final gains were $K_p = 1.1$, $K_i = 0.001$, and $K_d = 0.05$, and the same fixed gain set was used for all load conditions. The controller output determined the drive-command magnitude, while the sign of the position error selected the phase reconfiguration state. A lower bound was imposed on the transmitted magnitude. During commissioning, and before controller tuning, the actuator was operated with progressively increasing open-loop drive-command values; no output rotation was obtained below a value of approximately 15 to 17, and motion began only once this level was exceeded. This threshold arises from the neutral band of the electronic speed controller combined with the breakaway friction of the planetary stage. A floor of 20 was therefore applied to the transmitted magnitude so that the actuator would respond throughout the trajectory, and the proportional–integral–derivative output governed the command only where it exceeded this floor. The transmitted magnitude was consequently

equal to the floor for most of each test, and the controller acted principally near the extremes of the trajectory.

The control algorithm was implemented in MATLAB/Simulink and executed on an Arduino Mega 2560 using the Simulink Support Package for Arduino Hardware. The Simulink model was compiled and deployed to the Arduino board, which communicated with the host computer through External Mode over the USB serial connection. External Mode allowed the closed-loop controller to run in real time on the Arduino, while the reference position, encoder-measured position, ServoWrite command, and phase reconfiguration signal were monitored and logged on the host, and it also enabled controller parameters such as PID gains to be adjusted online during tuning without recompiling the model. Within this structure, the Arduino read the incremental encoder, computed the PID control action, generated the ServoWrite (PWM) command sent to the electronic speed controller, and produced the logic signal that triggered the triac-based phase reconfiguration circuit. MATLAB R2025b/Simulink therefore served as the model-based development and monitoring environment, while the Arduino performed the embedded real-time execution of the controller. At the beginning of the test, an initialisation signal was applied to align the electronic speed controller. After this initialisation interval, the reference position command was applied, and the closed-loop response was recorded (Figure 6). The model was executed with a fixed step of 10 ms, so the position estimate, the drive command, and the phase state were all updated at 100 Hz. The sequence of operations performed at each step and the division of tasks between the host model and the target board are summarised in Figure 7.

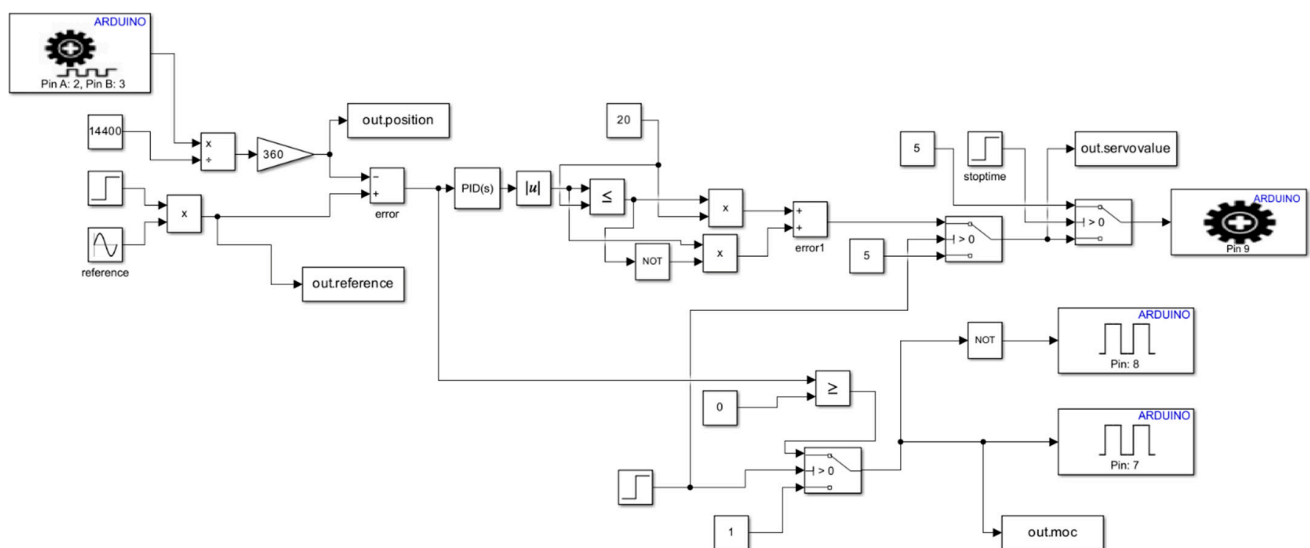


Figure 6. MATLAB Simulink control diagram of the actuator system.

4.8. Experimental Setup

The experimental setup was prepared to evaluate the actuator response under different loading conditions (Figure 8). The actuator was fixed on an aluminium profile structure, and a 25 cm moment arm was connected to the gearbox output. The output rotation axis and the $\pm 90^\circ$ range of motion covered by the reference trajectory are indicated in Figure 8.

Three known masses (250 g, 500 g, and 1 kg) were suspended from the free end of a 25 cm moment arm, and gravity applied a downward force, as illustrated in Figure 8. The gravitational load torque varies with arm angle. When θ is measured from the horizontal configuration, the torque magnitude is $\tau(\theta) = mgL \cos \theta$, where m is the suspended mass, g is gravitational acceleration, and $L = 0.25$ m is the moment arm length. Accordingly, the

three masses produce nominal maximum torques of approximately 0.61 Nm, 1.23 Nm, and 2.45 Nm at $\theta = 0^\circ$, when the arm is horizontal; the torque decreases as the arm rotates away from this configuration. These values are therefore nominal gravitational load levels rather than constant torques throughout the trajectory. The maximum test load was limited to 1 kg to reduce the risk of damage to the additively manufactured PLA gears. For each load condition, the reference trajectory, encoder-derived position estimate, motor command, and phase reconfiguration signal were recorded. The reference trajectory was a sinusoid of 90° amplitude and 0.5 Hz frequency; that is, $\theta_r(t) = 90^\circ \sin(\pi t)$, applied for two complete periods after the controller initialisation interval. Because the reference is continuously in motion, a steady state is never reached, and a steady-state error is not defined for this trajectory; performance was therefore summarised using peak excursion beyond the reference amplitude, the rise time of the initial transient, and the root-mean-square, mean absolute, and maximum values of the tracking error, together with the amplitude ratio and the phase lag between the reference and the estimated response. The phase lag was originally determined graphically from the horizontal separation between the reference and the response at their zero crossings. Because only three usable zero crossings occur within the two recorded periods, that estimate has a standard deviation of the order of 15 ms, and the values it produces are not ordered consistently with load. In this revision, the phase lag was therefore recomputed from the phase difference of the 0.5 Hz fundamental component of the two signals, evaluated over the whole motion interval. The two methods agree to within the scatter of the graphical estimate, and the spectral estimate is reported here.

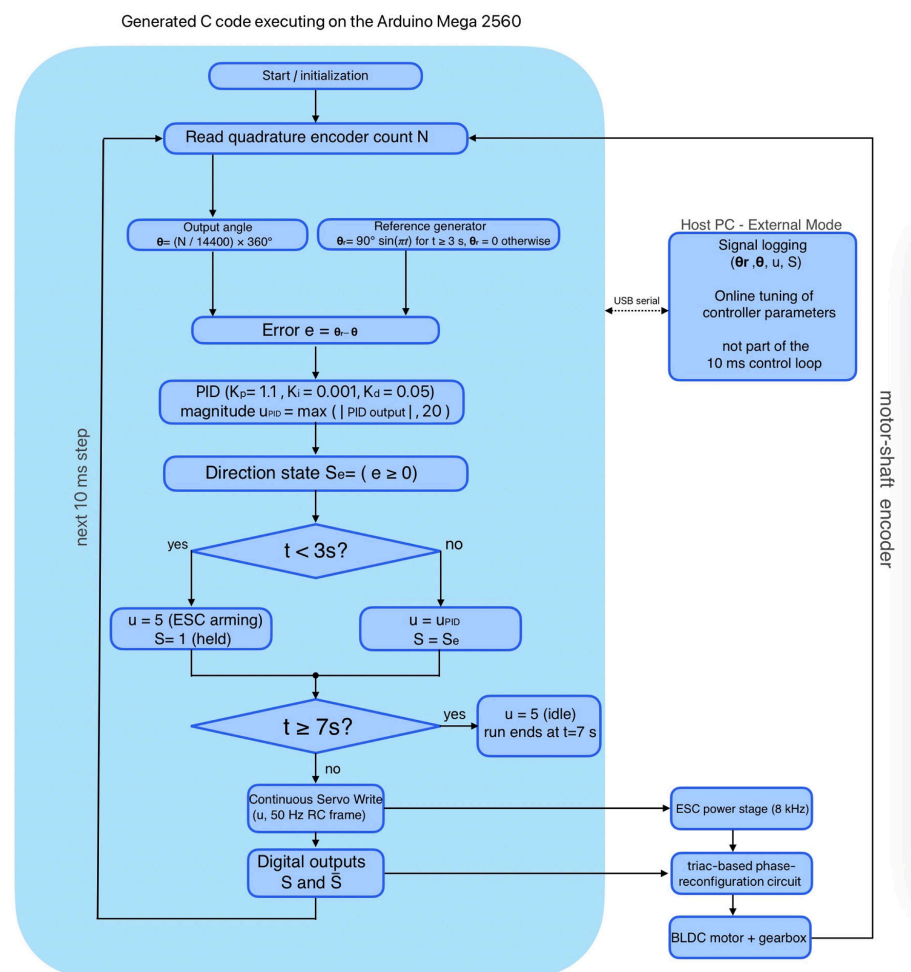


Figure 7. Flowchart of the control algorithm, showing the operations performed at each 10 ms step in the host model and the corresponding functions executed on the target board.

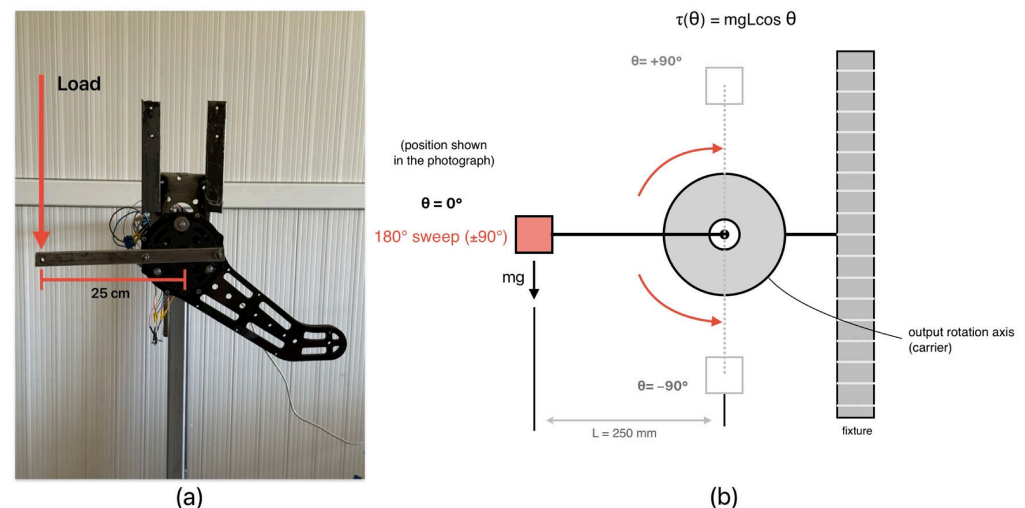


Figure 8. Experimental setup: (a) photograph of the arrangement, with the moment arm at the horizontal position; (b) schematic of the single output degree of freedom, showing the output rotation axis, the $\pm 90^\circ$ range covered by the reference trajectory, and the angular dependence of the gravitational load. The arrangement was used for the load-based actuator performance tests.

5. Experimental Results and Discussion

The experimental evaluation investigated the load-dependent encoder-derived position response of the proposed modular actuator. The actuator was tested with a 25 cm moment arm and suspended masses of 250 g, 500 g, and 1 kg. These conditions correspond to nominal maximum gravitational torques of approximately 0.61 Nm, 1.23 Nm, and 2.45 Nm, respectively, at the horizontal arm configuration. For each condition, the reference trajectory, encoder-derived position estimate, ServoWrite command, and phase reconfiguration signal were recorded. The first 3 s of each test corresponded to the electronic speed controller initialisation interval; the subsequent response was used for performance evaluation.

5.1. Load-Dependent Position Tracking Performance

The reference trajectories and encoder-derived position estimates obtained under the three suspended mass conditions are shown in Figure 9. The estimated position followed the reference trajectory in all reported bench tests, demonstrating proof-of-concept closed-loop operation across the tested load range. Because the feedback sensor was mounted on the motor shaft, these plots should not be interpreted as direct measurements of output-shaft position.

Representative control and phase reconfiguration signals for the nominal 1.23 Nm condition are shown in Figure 10. This condition was selected because it produced the lowest peak excursion among the three reported tests. Figure 10a shows the drive command transmitted to the electronic speed controller, and Figure 10b shows the logic signal applied to the optocoupler inputs of the phase reconfiguration circuit. The command trace shows the behaviour described in Section 4.7: the transmitted magnitude remains at the imposed floor of 20 for 81% to 85% of the samples in the motion interval, rising above it only near the extremes of the trajectory, where it reaches 33.6, 40.4, and 46.4 for the three load conditions.

Table 2 reports the peak excursion, the rise time of the initial transient, and the root-mean-square tracking error for the three load conditions, and Table 3 reports the complementary error, amplitude, and phase metrics. The peak excursion, defined as the amount by which the estimated position exceeds the 90° reference amplitude, was smallest under the nominal 1.23 N·m condition at 1.95° , compared with 3.4° and 3.05° for the lighter and heavier loads. This ordering is not monotonic with load and, given that each condition

was recorded once, it should not be interpreted as a systematic effect; repeated trials would be required before such a difference could be regarded as reproducible.

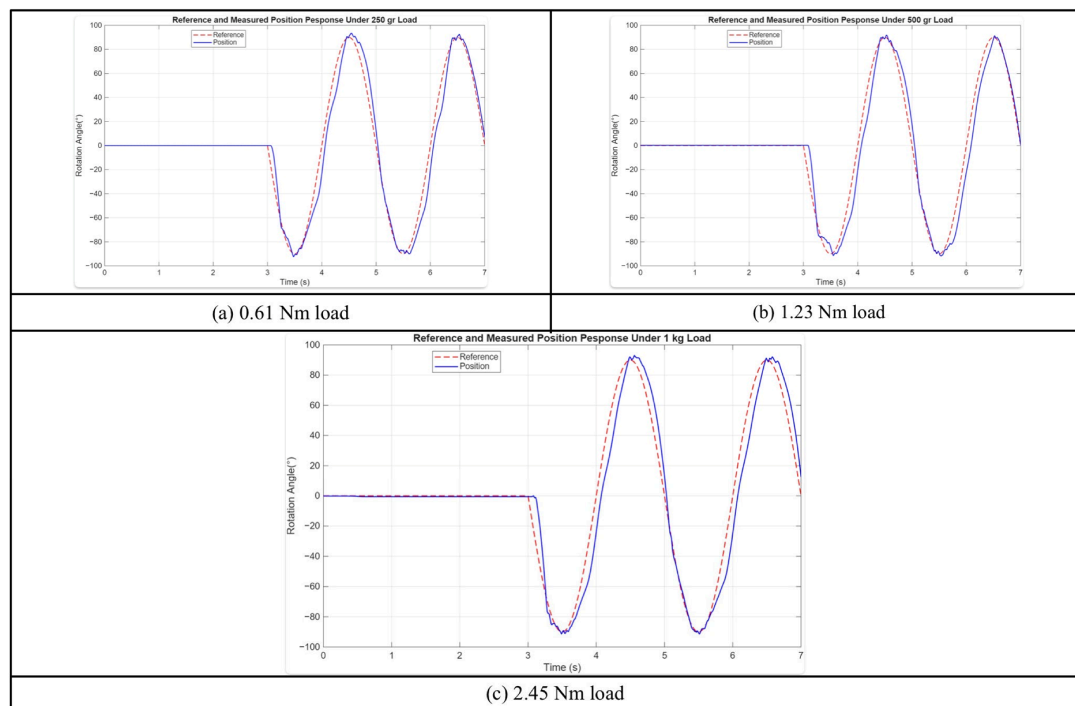


Figure 9. Reference trajectories and encoder-derived estimated output angle responses under the three suspended mass conditions: (a) nominal 0.61 Nm, (b) nominal 1.23 Nm, and (c) nominal 2.45 Nm at the horizontal arm configuration.

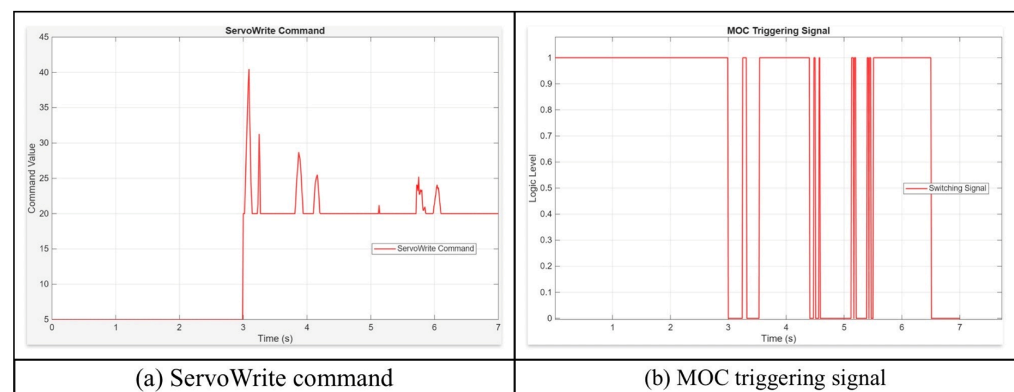


Figure 10. Representative control and phase reconfiguration signals under the 1.23 Nm load condition: (a) drive command transmitted to the electronic speed controller and (b) logic signal applied to the optocoupler (MOC) inputs, whose outputs trigger the triac gates and thereby interchange two motor phases to select the direction of rotation. Panel (b) shows the commanded phase state only; it is not a measurement of the electrical or mechanical reversal dynamics of the motor, which were not characterised in this study.

Table 2. Performance metrics of the encoder-derived position response under different suspended mass conditions.

Nominal Maximum Load Torque	Maximum Overshoot (°)	Rise Time (s)	RMS Tracking Error (°)
0.61 Nm	3.4	0.29	12.4
1.23 Nm	1.95	0.32	13.3
2.45 Nm	3.05	0.18	15.0

Table 3. Complementary tracking metrics of the encoder-derived position response over the motion interval.

Nominal Maximum Load Torque	Mean Absolute Error (°)	Maximum Absolute Error (°)	Amplitude Ratio (–)	Phase Lag (ms)
0.61 N·m	9.5	25.4	1.038	53
1.23 N·m	10.4	26.7	1.022	58
2.45 N·m	11.9	30.9	1.034	66

The tracking error metrics, in contrast, vary monotonically with load. The root-mean-square tracking error increased from 12.4° at 0.61 N·m to 13.3° at 1.23 N·m and 15.0° at 2.45 N·m, the mean absolute error increased from 9.5° to 10.4° and 11.9°, and the maximum absolute error increased from 25.4° to 26.7° and 30.9°. The phase lag between the reference and the estimated response increased correspondingly from 53 ms to 58 ms and 66 ms, equivalent to 9.6°, 10.4°, and 11.8° of the 0.5 Hz fundamental. The amplitude ratio remained close to unity in all three cases, between 1.022 and 1.038, indicating that the degradation appears as an increasing delay rather than as an attenuation of the motion amplitude. Since the same fixed gain set was used throughout, this consistent ordering across three independent metrics quantifies how the single-gain-set tracking performance deteriorates as the gravitational load is increased and supports the use of load-dependent tuning or gain scheduling in future work.

The nominal 2.45 N·m condition produced the shortest rise time of the initial transient, 0.18 s, compared with 0.29 s and 0.32 s for the lighter loads. The maximum drive command also increased with the suspended mass, reaching 33.6, 40.4, and 46.4, respectively. Since motor current and output torque were not measured, the mechanism responsible for the shorter rise time under the heaviest load cannot be established from the present data and is left as an open question. It is noted that the initial transient begins from the horizontal arm position, at which the gravitational torque assists the commanded direction of motion, so the rise time and the tracking metrics describe different aspects of the response and need not be ordered in the same way.

The gravitational load acting on the actuator is not constant during a test. Because the moment arm rotates through the full range of the reference trajectory, the load torque follows $\tau(\theta) = mgL \cos \theta$ and therefore varies between its nominal maximum at the horizontal position and approximately zero at the vertical positions, twice per period. Figure 11 shows this variation, computed from the measured position estimates for the three conditions. The values of 0.61, 1.23, and 2.45 N·m used to label the test conditions are nominal maxima at $\theta = 0^\circ$, not constant loads; the corresponding mean absolute load torques over the motion interval are 0.28, 0.57, and 1.11 N·m. The fixed gain set therefore operates against a continuously varying load throughout each test.

The frequency content of the response was examined over the motion interval, which comprises two complete periods of the reference sampled at 100 Hz. Figure 12 shows the amplitude spectra of the position estimate and of the tracking error. In both cases, the fundamental component at 0.5 Hz dominates, and the total harmonic distortion of the position estimate is 8.3%, 6.8%, and 9.8% for the three load conditions. The residual content is distributed broadly rather than concentrated at a small number of harmonics, which is consistent with the discontinuous nature of the drive: the transmitted magnitude is held at its floor for most of the trajectory, and the phase state is re-evaluated at every 10 ms step. The frequency resolution is limited to 0.25 Hz by the four-second duration of the motion interval, so these spectra should be regarded as indicative of the distribution of the residual content rather than as a precise harmonic characterisation.

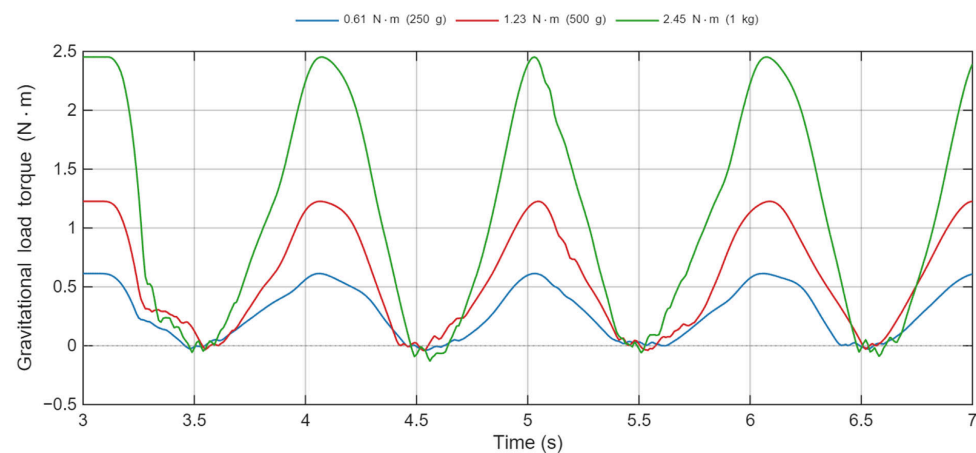


Figure 11. Gravitational load torque during the motion interval, computed from the measured position estimate as $\tau(\theta) = mgL \cos \theta$ for the three suspended mass conditions.

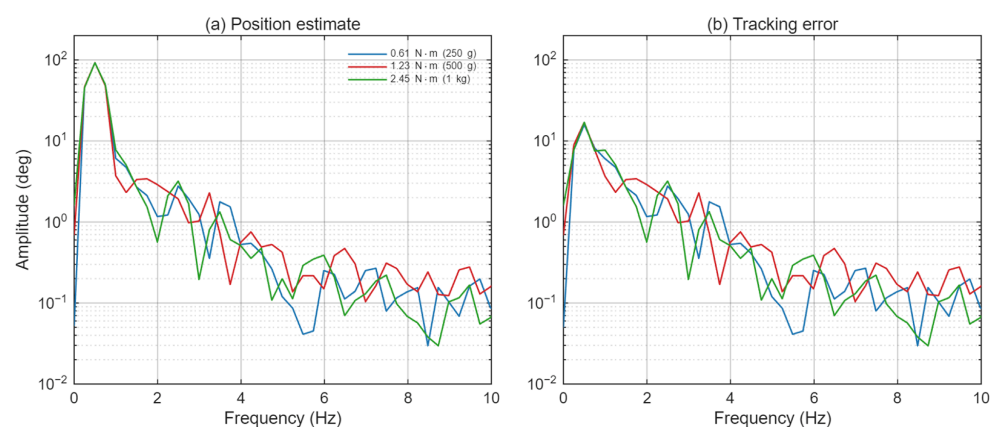


Figure 12. Amplitude spectra over the motion interval for the three load conditions: (a) estimated output angle and (b) tracking error.

The phase reconfiguration signal was re-evaluated at every controller step, and the recorded logic signal changed state 22, 18, and 21 times during the 4-second motion interval for the three load conditions, although the reference trajectory itself reverses direction only four times. The shortest interval between successive changes of state was a single 10 ms sample, and 13, 9, and 11 of the intervals were shorter than 50 ms. This repeated switching occurs where the tracking error changes sign, and it means that the phase interchange is commanded far more frequently than the trajectory requires. In none of the recorded transitions was the drive command at its idle value at the instant of switching. The consequences of this behaviour for the drive electronics were not measured and are discussed in Section 5.2.

Overall, the reported bench tests demonstrated encoder-derived trajectory tracking under three suspended mass conditions, with a consistent and monotonic degradation of tracking accuracy and an increasing phase lag as the load was raised. Together with the load capacity assessment in Section 4.5, which identifies surface durability rather than tooth bending as the constraint that governs the usable torque range of the printed transmission, these results delimit the operating range within which the present low-cost package is usable. Further evaluation should include repeated trials, direct output-shaft sensing, measurement of motor current and of the switching event, and load-dependent or adaptive control.

5.2. Limitations

Several limitations should be considered when interpreting the results. First, the incremental encoder was mounted on the motor shaft; therefore, the plotted response represents a gear-ratio-converted motor-side estimate rather than a direct measurement of the carrier/output-shaft angle. Gearbox backlash, torsional deformation, and load-dependent transmission error were not measured directly. Second, the suspended masses generated angle-dependent gravitational loading rather than constant torque, and the reported torque values correspond to nominal maxima at the horizontal arm configuration. Third, the tests characterise short-duration benchtop behaviour and do not establish long-term durability, thermal performance, electrical safety, or suitability for direct human interaction. Fourth, the electrical behaviour of the phase reconfiguration arrangement was not characterised. Motor phase currents, switching-transient voltages, and the response of the output stage of the electronic speed controller during and after each phase interchange were not measured, and the instant at which the triacs actually changed state was not observed. Since the recorded data show that phase interchange was commanded while the drive was active, and commanded considerably more often than the trajectory reverses, this characterisation is a prerequisite for any use of the arrangement beyond low-speed bench conditions, and for any assessment of the electrical stress imposed on the motor windings and on the controller. Fifth, each load condition was recorded once over two periods of the reference trajectory, so no repeated trial statistics are available, and differences between conditions that are not monotonic should not be treated as systematic. Sixth, the load capacity assessment in Section 4.5 is analytical: the stresses were computed from the nominal gear geometry and from published material properties for fused-deposition-manufactured PLA and were not verified by strain measurement, wear testing, or testing to failure. The present findings should therefore be interpreted as a proof-of-concept benchtop validation.

6. Conclusions

This article presented a modular brushless direct-current actuator prototype intended for upper-extremity rehabilitation research. The actuator integrates a brushless direct-current motor, a custom 7.2:1 planetary gearbox, motor-shaft encoder feedback, a commercial RC-type electronic speed controller, and an external triac-based phase reconfiguration circuit. The external circuit separates direction selection from drive-command magnitude so that the controller's native reverse-entry sequence is not invoked; it is an implementation element of the prototype rather than a characterised drive stage, and it is not claimed as a novel power electronic topology. The gearbox reduces the motor speed and increases the available output torque, while the outer PID loop regulates a gear-ratio-converted position estimate derived from the motor-shaft encoder.

The reported bench tests demonstrated reference-trajectory tracking under suspended mass conditions corresponding to nominal maximum gravitational torques of approximately 0.61 Nm, 1.23 Nm, and 2.45 Nm at the horizontal arm configuration. A sinusoidal reference of 90° amplitude at 0.5 Hz was followed in all three conditions. Under a single fixed gain set, the root-mean-square tracking error increased monotonically with load, from 12.4° to 13.3° and 15.0°, and the phase lag increased from 53 ms to 58 ms and 66 ms, while the amplitude ratio remained close to unity; the degradation therefore appears as an increasing delay rather than as an attenuation of the motion. A load capacity assessment of the printed planetary stage indicates that the tooth-root bending stress remains an order of magnitude below the strength of the material, whereas the Hertzian contact stress approaches the range accepted for continuous operation of polymer gears, so surface durability governs the usable torque range and accounts for the 1 kg test limit. Direct

output-shaft measurements and repeated trial statistics are needed before the differences between conditions can be generalised.

The representative command and phase reconfiguration signals indicate that bidirectional bench operation was obtained by separating drive-command magnitude from direction selection. This proof-of-concept arrangement retained compatibility with the selected electronic speed controller and avoided repeated dependence on its internal reverse-entry sequence. Its electrical behaviour, however, was not characterised: phase interchange was commanded while the drive was active and considerably more often than the trajectory reverses, and the resulting stress on the motor windings and on the output stage of the controller remains unquantified. The arrangement was therefore not evaluated as a safety-rated drive architecture for human interactive use, and its electrical characterisation is the first requirement for further development.

Before integration into a rehabilitation device, future work should include an independent output-shaft encoder, repeated trials with statistical reporting, gearbox backlash and efficiency measurements, long-duration wear and thermal tests, motor-current and switching-transient measurements, fault handling, and validation under representative joint trajectories. Stronger transmission materials and load-dependent or adaptive control strategies should also be investigated.

This article was derived from the master's thesis, titled "Original Modular Actuator Design for Upper Extremity Rehabilitation Devices," conducted under the supervision of Assoc. Prof. Dr. Alper Kadir Tanyıldızı in the Department of Mechatronics Engineering, Faculty of Engineering, Firat University.

Author Contributions: Conceptualization, B.E. and A.K.T.; methodology, B.E.; software, B.E.; validation, B.E. and A.K.T.; formal analysis, B.E.; investigation, B.E.; resources, A.K.T.; writing—original draft preparation, B.E.; writing—review and editing, B.E. and A.K.T.; visualization, B.E.; supervision, A.K.T.; project administration, A.K.T.; funding acquisition, A.K.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Firat University Scientific Research Projects Coordination Unit (FÜBAP) under project number MF.26.02.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The experimental data and supporting design files are available from the corresponding author upon reasonable request.

Acknowledgments: This article was derived from the master's thesis of B.E., conducted under the supervision of A.K.T. in the Department of Mechatronics Engineering, Faculty of Engineering, Firat University.

Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

Symbol	Description
b	Gear face width (mm)
$e(t)$	Position error ($^{\circ}$)
g	Gravitational acceleration (m s^{-2})
i	Planetary reduction ratio (–)
K_d, K_i, K_p	Derivative, integral, and proportional gains of the PID controller
K_t	Motor torque constant ($\text{N} \cdot \text{m A}^{-1}$)
K_V	Motor speed constant (rpm V^{-1})

L	Moment arm length (m)
m	Suspended mass (kg)
N	Accumulated quadrature encoder count (–)
S	Phase reconfiguration state (–)
u(t)	Drive-command magnitude (–)
Y	Lewis form factor (–)
Z _p , Z _r , Z _s	Tooth numbers of the planet, ring, and sun gears (–)
θ , θ_r	Estimated output angle and reference angle (°)
σ , σ_H	Tooth-root bending stress and Hertzian contact stress (MPa)
τ	Gravitational load torque (N·m)
ν	Poisson ratio (–)
BLDC	Brushless direct current
ESC	Electronic speed controller
FDM	Fused-deposition modelling
PID	Proportional–integral–derivative
PLA	Polylactic acid
PWM	Pulse-width modulation
RMS	Root-mean-square

References

- Sanchez, R.J.; Liu, J.; Rao, S.; Shah, P.; Smith, R.; Rahman, T.; Cramer, S.C.; Bobrow, J.E.; Reinkensmeyer, D.J. Automating arm movement training following severe stroke: Functional exercises with quantitative feedback in a gravity-reduced environment. *IEEE Trans. Neural Syst. Rehabil. Eng.* **2006**, *14*, 378–389. [\[CrossRef\]](#) [\[PubMed\]](#)
- Ragonesi, D.; Agrawal, S.; Sample, W.; Rahman, T. Series elastic actuator control of a powered exoskeleton. In *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Boston, MA, USA, 30 August–3 September 2011*; IEEE: New York, NY, USA, 2011; pp. 3515–3518.
- Carignan, C.; Liszka, M.; Roderick, S. Design of an arm exoskeleton with scapula motion for shoulder rehabilitation. In *Proceedings of the 12th International Conference on Advanced Robotics (ICAR), Seattle, WA, USA, 18–20 July 2005*; IEEE: New York, NY, USA, 2005; pp. 524–531. [\[CrossRef\]](#)
- Sugar, T.G.; He, J.; Koeneman, E.J.; Koeneman, J.B.; Herman, R.; Huang, H.; Schultz, R.S.; Herring, D.E.; Wanberg, J.; Balasubramanian, S.; et al. Design and control of RUPERT: A device for robotic upper extremity repetitive therapy. *IEEE Trans. Neural Syst. Rehabil. Eng.* **2007**, *15*, 336–346. [\[CrossRef\]](#) [\[PubMed\]](#)
- Frisoli, A.; Borelli, L.; Montagner, A.; Marcheschi, S.; Procopio, C.; Salsedo, F.; Bergamasco, M.; Carboncini, M.C.; Tolaini, M.; Rossi, B. Arm rehabilitation with a robotic exoskeleton in virtual reality. In *Proceedings of the IEEE 10th International Conference on Rehabilitation Robotics (ICORR), Noordwijk, The Netherlands, 13–15 June 2007*; IEEE: New York, NY, USA, 2007; pp. 631–642. [\[CrossRef\]](#)
- Berdal, J.B.; Hartnett, R.J.; Quintero, D. UP-CARE: An upper limb portable cable assistive recovery exoskeleton for elbow movement assistance. In *Proceedings of the 2025 International Conference on Rehabilitation Robotics (ICORR), Chicago, IL, USA, 12–16 May 2025*; IEEE: New York, NY, USA, 2025; pp. 1835–1840. [\[CrossRef\]](#) [\[PubMed\]](#)
- KhalilianMotamed Bonab, A.; Camardella, C.; Frisoli, A.; Chiaradia, D. Hybrid soft-rigid elbow exosuit: Theory, mechatronic design, and experimental assessment. *IEEE Trans. Robot.* **2026**, *42*, 912–930. [\[CrossRef\]](#)
- Aljarah, A.; Awad, M.I.; Boushaki, M.; Hussain, I. Design optimization of a variable stiffness actuator for knee exoskeleton application. *IEEE Access* **2023**, *11*, 52740–52749. [\[CrossRef\]](#)
- Mondal, S.; Mitra, A.; Chattopadhyay, M. Mathematical modeling and simulation of brushless DC motor with ideal back-EMF for precision speed control. In *Proceedings of the IEEE International Conference on Electrical, Computer and Communication Technologies (ICECCT), Coimbatore, India, 5–7 March 2015*; IEEE: New York, NY, USA, 2015; pp. 1–5.
- Ergezgin, B. Original Modular Actuator Design for Upper Extremity Rehabilitation Devices. Master’s Thesis, Department of Mechatronics Engineering, Fırat University, Elazığ, Türkiye, 2025.
- Wensing, P.M.; Wang, A.; Seok, S.; Otten, D.; Lang, J.; Kim, S. Proprioceptive actuator design in the MIT Cheetah: Impact mitigation and high-bandwidth physical interaction for dynamic legged robots. *IEEE Trans. Robot.* **2017**, *33*, 509–522. [\[CrossRef\]](#)
- Kau, N.; Schultz, A.; Ferrante, N.; Slade, P. Stanford Doggo: An open-source, quasi-direct-drive quadruped. In *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA), Montreal, QC, Canada, 20–24 May 2019*; IEEE: New York, NY, USA, 2019; pp. 6309–6315. [\[CrossRef\]](#)

13. HobbyKing. HobbyKing X-Car 120A Brushless Car ESC (Sensored/Sensorless). Available online: <https://hobbyking.com/hobbykingr-x-car-120a-brushless-car-esc-sensored-sensorless.html> (accessed on 22 July 2026).
14. ODrive Robotics. Controller. ODrive Documentation. Available online: <https://docs.odriverobotics.com/v/latest/manual/control.html> (accessed on 22 July 2026).
15. HobbyKing. *HobbyKing Brushless Electronic Speed Control for Car or Truck—User Manual*; HobbyKing: Hong Kong, China, 2009.
16. López García, P.; Crispel, S.; Saerens, E.; Verstraten, T.; Lefeber, D. Compact gearboxes for modern robotics: A review. *Front. Robot. AI* **2020**, *7*, 103. [[CrossRef](#)] [[PubMed](#)]
17. Yoshida, T.; Endo, G.; Okubo, A.; Nabae, H. Experimental evaluation of a quasi-direct-drive actuator with a 3D-printed planetary gear reducer. In *Proceedings of the IEEE/SICE International Symposium on System Integration (SII), Atlanta, GA, USA, 17–20 January 2023*; IEEE: New York, NY, USA, 2023; pp. 1–6. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.