WRIST REHABILITATION EXOSKELETON

THESIS

Submitted in Partial Fulfillment of

the Requirements for

the Degree of

MASTER OF SCIENCE, MECHATRONICS AND ROBOTICS

at the

NEW YORK UNIVERSITY
TANDON SCHOOL OF ENGINEERING

by

HARSHAVARDHAN SANJIV VBHANDIK

May 2025

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Vita

Harshavardhan Sanjiv Vibhandik was born in Dhule, Maharashtra, India, where he completed his early schooling at Canossa Convent High School. In 2022, he completed his undergraduate studies - Bachelor of Technology in Electronics (Minor in Robotics) from the Maharashtra Institute of Technology Academy of Engineering, Alandi, Pune. During his bachelor's studies, he completed internships at HunarPro Skilling Hub and Lucy Electric. He designed and developed a prototype of a Medical Assistant Robot as his capstone research, which was later approved for real-time testing in the local government hospital during the COVID-19 pandemic to maintain the necessary precautions. He joined the R&D of IIT Ropar, India, as a Research Intern for a semester-long internship, and impressed by his performance following his bachelor's, he got an offer to join there as a Research Engineer. In February 2023, he transitioned to I-Hub AWaDH, IIT Ropar as a Manufacturing engineer before leaving in August 2023 for his graduate studies.

Harshavardhan started his Master of Science in Mechatronics and Robotics in September 2023. There, he began his research on the Robotic Wrist Rehabilitation Exoskeleton in June 2024, and it continues onward. The research was conducted at the MERIIT Laboratory at NYU.

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ABSTRACT

WRIST REHABILITATION EXOSKELETON

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Advisor: Prof. Rui Li

Submitted in Partial Fulfillment of the Requirements for

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May 2025

People suffer from central dysfunction of wrist movements that occur due to neurological conditions, especially stroke, which creates significant functional limitations for daily activities. The effective recovery of patients requires externally guided movements, feedback monitoring, and activity progression, which correspond to the patient's current rehabilitation level. Traditional physiotherapy stands as a fundamental recovery method. However, its practical use is limited by the executive shortage, along with substandard intensity control and the lack of objective performance monitoring systems. Academic research has turned to intelligent robotic systems for patient-centric rehabilitation due to their capacity to deliver task-specific exercise treatments. This research aims to develop a modern, innovative, sensor-integrated rehabilitation system focused on wrist joint motor recovery. Rehabilitation technology developed through this research enables users to engage in multisensory interaction and produce wrist motions naturally. The objective is to establish a link between medical precision requirements and user-friendly patient devices, thereby achieving treatments that meet both functional criteria and accessibility needs. This attempt requires a conceptual union between biomechanical ergonomics, rehabilitative research, and human motor learning. The research highlights practical challenges in translating laboratory advancements into usable biomedical tools, particularly in terms of system portability and the need for modular design in home-based therapeutic equipment that requires user-friendly interfaces. The primary focus is on the potential for sensory input to accelerate neurological growth and enhance voluntary mobility. The wrist rehabilitation exoskeleton is equipped with a multimodal sensor system, enabling real-time adjustment of assistance scenarios during therapeutic procedures. The advanced biomechanical sensor network provides data on muscle activities, joint forces, and movement angles. The system receives inputs from various sources and utilizes its control mechanisms to understand user needs and adjust the output torque accordingly. Multiple sensor modalities operating within a single feedback system enable precise motion tracking while adjusting torque outputs to accommodate specific user physical capabilities. The device's ability to change itself finely through sensor information constitutes its baseline intelligent assist-as-needed function, which promotes security and rehabilitative success. We developed a comprehensive rehabilitation system, which began

with building the basic mechanical structure and progressed to implementing dynamic control systems. Then, we implemented the adaptive feedback and initial user testing to establish an extensive rehabilitation solution. Ultimately, the research led to the development of next-generation rehabilitation technology, which enhances patient capabilities and enables practitioners to develop neurorehabilitation solutions through evidence-based engineering approaches.

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Chapter 1: Introduction

Introduction 1.1

Rehabilitation serves as a fundamental procedure for achieving recovery after neurological injuries affecting stroke, traumatic brain injury (TBI), and spinal cord injury patients. Upper-limb rehabilitation is a crucial area of rehabilitation because the recovery of hand and wrist motor function significantly impacts personal capabilities in executing daily routines. These deficits create long-term functional disabilities that decrease both independence levels and living standards. Wrist rehabilitation has particular considerations because its movements present complex coordination challenges between wrist and hand functions. Robot-assisted rehabilitation devices are in increasing demand because they provide precisely planned therapeutic movements to enhance therapeutic outcomes.

The discipline of rehabilitation robotics has achieved considerable advancements in recent years through its endeavors to create exoskeletons that aid in motor rehabilitation for individuals with disabilities affecting the hand and wrist. These exoskeletons are worn by patients to aid hand and wrist mobility during rehabilitation and to facilitate controlled motor activity that helps enhance rehabilitation. Various technical challenges prevent the exoskeleton technologies from spreading efficiently into the market for broader patient applications. From the perspective of device usability and maintainability, four fundamental challenges are ergonomics, usability, sensor integration, and adaptive control systems. Device effectiveness and patient acceptance both require these elements.

The current wrist exoskeleton systems show remarkable advancement in their mechanical constructs and operational capabilities. The health technology systems aim to improve joint flexibility through range of motion (ROM) improvements while minimizing robot resistance forces and generating sufficient torque to achieve therapeutic objectives. Despite achieving sufficient operational capability, the devices currently struggle to deliver essential real-time adaptive feedback to patients. The ability of patients to use the devices independently outside clinical settings remains limited because most of these medical systems lack adequate capacity to function without supervised monitoring. To enhance their application, additional work is needed on the mechanical structure of such devices to create lightweight products that provide user-friendly solutions.

Sensor technologies, such as force/torque sensors and electromyography (EMG) sensors, combined in rehabilitation exoskeletons, can contribute to addressing existing challenges. These sensors provide real-time feedback to the device, enabling it to adjust its assistance according to the user's accomplishments and fatigue state. The control system of these devices operates using machine learning algorithms to produce real-time movements in response to changing human intentions. Sensor-based adaptive control systems might significantly enhance the performance of rehabilitation exoskeletons and maximize therapeutic outcomes for each patient.

Research Objectives and Scope 1.2

The primary purpose of this thesis is to develop and improve an exoskeletal design for the wrist to help patients recover motor skills after wrist impairment. The exoskeleton system aims to address current rehabilitation challenges in wrist therapy by enhancing existing systems' operational effectiveness, utilitarian design, and adaptive capabilities. The initiative will pursue three key objectives to achieve its goals.

1. Enhancing Range of Motion (ROM): One of the main shortcomings of current exoskeletons is their restricted range of motion, especially in flexion/extension and pronation/supination movements. This study aims to optimize the exoskeleton's range of motion to more closely mimic normal wrist motion, enabling patients to undertake everyday activities.
2. Reducing Friction and Inertia: Mechanical friction and inertia can significantly hinder the smoothness of movement in wrist exoskeletons, causing pain and rendering therapy less effective. Through optimal mechanical exoskeleton design, the project aims to minimize friction and reduce inertia at key joints, including the flexion/extension and radial/ulnar deviation joints.
3. Integrating Real-Time Adaptive Feedback: Exoskeletons currently available on the market suffer from restricted joint movement capabilities, particularly in extending and bending (flexion/extension) and rotating the wrist (pronation/supination). The objective of this research is to expand the range of wrist movement in exoskeletons, enabling patients to perform regular, everyday tasks.

Incorporating these enhancements will improve the wrist exoskeleton's design for medical and home therapy settings. The project's objective is to develop an accessible, user-friendly, and lightweight design that can be employed by patients with other physical disabilities and those with strength or dexterity constraints.

Broader Impact 1.3

A robust, adaptable wrist exoskeleton holds promise to transform therapeutic practices radically. These practices help people with neurological disorders recover after stroke, Parkinson's disease, or spinal cord injuries. These devices will help patients improve their outcomes by increasing patient participation and adherence to therapy, lessening the strain on healthcare systems, and improving patients' quality of life.

Furthermore, this project offers insights into the broader field of assistive robotics by addressing some fundamental issues inherent to sensor fusion, control systems, and adaptive feedback processes. The successful implementation of real-time, customized feedback for rehabilitation exoskeletons may yield key insights toward developing future wearable robots for rehabilitation and total assistive use in everyday living. Lastly, the project will find its purpose in providing more efficient, affordable, and accessible rehabilitation technologies to aid patients in regaining independence and improving their motor functions.

Chapter 2: Literature Review

Sensor Technologies & Integration 2.1

Focus: EMG, IMU, EEG, force sensors, sensor fusion, intent detection.

Sensor fusion technology has been central to developing adaptive wrist rehabilitation systems. Sensor fusion, multimodality, and real-time bio-signal feedback have extensively relied on them in their ability to make inferences about user intent, monitor muscle behavior, and drive actuator control. Current evidence highlights the advantages of sensor-guided control schemes in optimizing response, enhancing user protection, and personalizing therapy.

One such avenue is the use of bioelectrical signals to drive assistive responses. For instance, surface-level muscle signal detection and neuromuscular stimulation experiments have demonstrated that using voluntary muscle activity to trigger robotic movement profoundly impacts neuroplastic recovery and reduces abnormal co-contractions in post-stroke patients. When tested across controlled rehabilitation protocols, such systems have shown improved performance in both functional motor tests and muscle coordination measures compared to conventional robotic assistance [8].

To support longer-term rehabilitation, hybrid control approaches have been developed based on dual bio-signals, such as electroencephalography (EEG) and electromyography (EMG). These systems dynamically adapt control strategies based on fatigue detection, allowing users to continue contributing even as muscle input begins to decrease. Low-cost deployments of consumer-grade wearable sensors have shown reasonable classification accuracy and real-time adaptability, albeit with the need to ensure signal stability and minimize the effect of motion artifacts and electrode movement [9].

Systematic reviews have also classified sensor environments in exoskeletons into functional categories, highlighting the complementary use of force sensors, inertial measurement units (IMUs), and neural signals to facilitate accurate motion control and user-invariant rehabilitation. Integrating such sensors facilitates feedback-driven compensation and serves as the premise for intent-determined, assist-as-needed modes. Prospective calibration drift, signal lag, and interference are prevalent problems in daily, dynamic activities [14, 36].

Myoelectric control systems remain popular due to their non-invasive nature and direct correspondence to voluntary motion. Recent work has incorporated machine learning and neural networks into predicting multi-degree-of-freedom limb movement from electromyography (EMG) inputs. Such systems, however, are limited by constraints in training data size, computation load, and subject variability in muscle behavior. We identified sensor fusion and adaptive modeling as the primary avenues for enhancing performance in heterogeneous patient populations [32].

Overall, today's wrist exoskeletons are more defined by their ability to detect, analyze, and act upon user feedback in real-time. Integrating sensors, whether hardware or control logic, remains key to providing individualized, efficient, and long-lasting rehabilitation outcomes.

Control Strategies (Adaptive, AAN, Intelligent) 2.2

Focus: Assist-as-needed, impedance, machine learning, real-time control.

Modern rehabilitation exoskeletons are increasingly driven by the need for innovative and adaptive control strategies that can respond to user intent, adjust for variability in physical abilities, and customize therapy in real-time. These control systems often merge bio-signal decoding, dynamic motion modeling, and real-time actuation adjustment to deliver assist-as-needed (AAN) aid and ensure user safety and participation throughout rehabilitation.

One fundamental development in this field is the integration of hierarchical control structures with three layers: perception, decision-making, and execution. The perception level generally utilizes multi-sensor sets, such as inertial units, muscle effort signals, and encoders, to recover motion intent. Decision-making algorithms then process this intent employing machine learning, fuzzy logic, or rule-based systems. These devices interpret voluntary user effort and deliver corresponding mechanical support [39].

The OpenWrist system showcases intelligent exoskeleton technology by developing mechanical systems that exceed wrist range of motion (ROM) standards and minimize device inertia and friction. However, the systems do not possess adaptive or individualized responses because they lack integrated force feedback or learning capacity. Research conducted since then has highlighted that improved sensor technology, paired with real-time feedback systems, will enhance the therapeutic effectiveness of exoskeletons [10].

To address intention-driven actuation, newer systems employ deep learning algorithms in conjunction with wearable bioelectronic sensors to deliver motion predictions with high accuracy. These models enable cloud-based control structures that perceive user intent and control exoskeleton motion with low latency. While such systems are promising for enabling multi-joint motion, e.g., elbow and wrist mobility, there are challenges related to real-time responsiveness and signal consistency, particularly in uncontrolled environments. Additionally, most such systems lack embedded torque sensing, which precludes them from dynamically modulating resistance based on user fatigue or strength in real-time [13].

Other implementations utilize control structures independent of force or EMG sensors, instead relying on real-time comparisons between simulated joint movement and actual movement data to estimate user effort. The devices utilize fuzzy logic and PID controllers to adjust motor output dynamically, providing low-cost, sensor-poor solutions for home-based or minimally supervised therapy [33].

Across the literature, adaptive control strategies, such as impedance-based control, AAN frameworks, and AI-based predictive models, remain at the forefront of designing upper-limb and wrist exoskeletons. Incorporating intelligent sensing and control schemes is continually highlighted as the path to developing innovative rehabilitation devices that respond to diverse user demands in real-time [40].

Mechanical Design & Structural Innovation 2.3

Focus: Mechanical transmission, torque delivery, ROM, joint design.

Wrist exoskeletons' effectiveness, user comfort, and practical usage rely on strong fundamental mechanical construction principles. Continuous advancements in materials, actuation systems, structural frames, and wearable elements continually reshape device designs, delivering accurate, safe, and sustainable rehabilitation care.

Passive rehab robots remain suitable for low-cost therapy delivery in resource-limited settings. One such instance involves a wrist rehab system constructed of open-source electronics and aluminum/ABS frames, which applies predefined motion patterns in flexion, extension, and radial-ulnar deviation. Finite Element Analysis (FEA) validated the structural stability under cyclic loading, and its Arduino-MATLAB-based control interface improved therapy exercise repeatability. However, due to the lack of sensory feedback and adaptive control, such systems are limited in offering individualized or progressive rehabilitation strategies [11].

Flex sensors are incorporated into exoskeletons to capture wrist movements during mirror therapy training, ensuring interactivity. In master-slave devices, the second hand is controlled by the first hand based on flex-sensor feedback to enable bilateral use. While lightweight and easy to manufacture using 3D-printed PLA, these devices are susceptible to motion accuracy issues due to sensor drift and the absence of force feedback. Without the integration of EMG or torque sensing, resistance levels are pre-programmed, and their ability to respond to the specific requirements of individual patients is impaired [12].

Several surveys over the last few decades have identified three major design problems in wearable exoskeletons: joint misalignment, rigidity-induced discomfort, and user disengagement. Accurate joint alignment can be achieved through the multi-DOF movement capability of exoskeletons, such as ARMin and RiceWrist, and feedback via real-time bio-signals derived from EMG. EEG and force sensors enable control method trajectory tracking and assist as-needed functionality with greater capability. Nonstandardized systems have issues with cross-comparison, which hinders their wider adoption among doctors in clinics [16].

Recent structural advancements emphasize natural biomechanics and energy efficiency. Compliant, beam-based hybrid systems, combined with soft actuators such as vacuum-activated elastomeric structures, offer functional motion and gravity compensation with reduced energy consumption. The configurations exhibit bistable states of motion and require minimal power to maintain wrist positions, reducing user fatigue during prolonged therapy [28].

Usability is increasingly being integrated as a core design element. Sincerely, portable wrist exoskeletons now come with ergonomic straps, one-handed wear, and sEMG-based intention identification. Lightweight construction, transparent control dynamics, and easy installation enable these systems for home-based, unsupervised rehabilitation, positioning human-centered design as the cornerstone of the next generation of exoskeleton development [37].

Wearable Wrist Exoskeleton Reviews 2.4

Focus: Reviews of devices, system classification, commercial analysis

The increasing wearability and user flexibility of rehabilitation and occupational assistance systems have largely dominated the last decade of wrist exoskeleton design. Comprehensive reviews of commercially available, research-grade devices reveal a strong interest in active exoskeletons that utilize electric motors and cable transmission systems. These systems offer improved torque control, but at the expense of mobility and comfort [15, 41].

Structural classification categorizes architectures into hard, compliant, and soft. Hard exoskeletons, while precise in control, may compromise anatomical alignment and wearability. Soft and compliant structures, however, have become acceptable since they are anatomically compatible and ergonomic. They are most suitable for home or unsupervised rehabilitation settings, where usability and comfort are essential for the user [15].

The most prevalent combination of motion-tracking sensing technologies in the surveyed systems includes force sensors, IMUs, and surface EMG elements. The sensors enable advanced Assistance-As-Needed (AAN) and Control Passive Motion (CPM) control methods through user ability-based rehabilitation intensity modulation. However, ongoing challenges persist in sensor fusion, motion prediction, and maintaining real-time adaptability under varying usage conditions [41, 42].

Despite technological advancements, there are limitations. Actuator bulk is an issue that commonly arises in most designs, affecting portability and joint alignment, which can lead to suboptimal rehabilitation outcomes. There is also a shortage of exoskeletons for occupational wrist support, with most research still focused on rehabilitation. Market adoption is also influenced by the lack of standardization in usability testing and the inadequacy of long-term clinical trials [41].

Bioelectrical and biomechanical sensors (e.g., EMG, EEG, FSR) are increasingly being utilized, with studies demonstrating that they significantly contribute to enhancing intent recognition and personalizing control. Machine learning algorithms like SVM and CNN are typically employed to improve signal classification and motion prediction. This further underscores the need for multimodal sensor fusion and AI-based adaptability [42, 43].

Clinical & Usability Studies 2.5

Focus: Stroke rehab trials, fit/comfort, subjective user testing

Clinical trials and usability testing are crucial for demonstrating wrist rehabilitation devices' efficacy and determining a patient-centered design. Several recent studies reveal how robot-assisted therapy, manual treatment techniques, and EMG-controlled return feedback systems enhance treatment outcomes for patients with neuromuscular impairment, stroke, or orthopedic trauma [1, 6].

Robotic treatment has demonstrated significant potential in enhancing motor ability and interaction. A randomized controlled trial comparing robotic rehabilitation by the WRISTBOT reported statistically significant improvements in range of motion, isometric force control, and function compared to standard therapy. The tolerance level and patient satisfaction rating were high, thus ensuring the future of intelligent rehabilitative machines as tools for offloading therapists and personalizing treatment algorithms [2].

As a complement to this, other studies have been grounded on manual mobilization methods in chronic hemiplegic stroke patients. Supplementing hands-on therapy with conventional physiotherapy significantly improved wrist extension, grip strength, and hand function. These findings underscore the relevance of biomechanical treatment, particularly in addressing capsular adhesions and contractures, where passive stiffness acts as a barrier to recovery [3].

Novel diagnostic paradigms have appeared to allow objective assessment tools. A new wrist-specific function test using inertial sensors has been presented in a pilot study to evaluate flexion-extension motion in ischemic stroke survivors. Patients demonstrated an increased range of motion when FES was added, while sensor-based evaluation was superior to standard clinical scales in identifying subtle motor impairments [6].

Usability testing also provided insight into how the application is used daily. The MyoGuide system, which utilizes mobile EMG-based feedback for training wrist extension, demonstrated high user satisfaction and flexibility among subacute stroke patients. While its game-like interface and dynamic difficulty adjustments helped encourage patient motivation, independent use and sensor placement challenges highlighted the need for further optimization for at-home rehabilitation [26].

Bio-signal Processing & Myoelectric Control 2.6

Focus: EMG/EEG-based systems, fatigue detection, intention modeling

Bio-signal processing plays a crucial role in enhancing the responsiveness and individualization of wrist rehabilitation exoskeletons. Surface electromyography (sEMG) remained favored in practice due to its non-invasive nature and close affinity with voluntary muscle contraction. Bilateral control-based systems, which involve sEMG signals of the sound arm to take over the crippled arm, were found to bring acceptable outcomes while inducing motor cortex regions and coordination of movement. One study achieved an accuracy rate of over 80% across various grip patterns, with angular tracking errors of less than 3.5%, validating its applicability for home-based and outpatient therapy [30].

Emerging substitutes, such as Force Myography (FMG), are robust complements or replacements for EMG, offering immunity to electrical noise and requiring minimal preprocessing. FMG uses muscle volumetric changes to detect intent and can be paired with machine learning classifiers like SVM and ANN for gesture recognition and real-time control. Although promising, technology remains to be clinically proven beyond healthy subject trials, and improvements in standardization and uniformity of sensor placement are needed [25].

Another line of research tackles enhancing feedback from multimodal haptic systems, such as the MuViSS device. The combination of vibrotactile and skin-stretch modalities on these systems enhances object perception and proprioception, which are essential for closed-loop control of motor tasks in prosthetics and exoskeletons. Users reported lower cognitive load and greater task accuracy when working with MuViSS than with standard force feedback [31].

Hybrid control techniques, with EEG-sEMG switching systems, also support extended therapy by compensating for muscle fatigue. A design achieved greater than 94% control accuracy using sEMG and switched to EEG-based commands upon fatigue, thereby maintaining therapeutic continuity through intention-based control [35].

Lastly, mechanical methods, such as Series Elastic Actuator (SEA)-based sensing, avoid relying on biological signals altogether, instead using angular deflection to infer user intention. Such systems are highly sensitive, with stable, compliant motion possible even with minimal supervision [38].

These developments suggest that rehabilitation systems powered by reliable bio-signal interpretation and real-time control will become more flexible, intuitive, and low-latency.

Haptic Feedback & Glove Interfaces in Post-Stroke Rehabilitation 2.7

Focus: Haptic gloves, vibrotactile systems, proprioceptive feedback

Haptic glove systems have been identified as promising wrist and hand rehabilitation tools. They utilize motor assistance and sensory return to facilitate complete recovery in stroke patients. They will likely incorporate sensor employment, actuators, and virtual reality interfaces as they involve, activate proprioception, and reeducate motor control.

New developments include systems that enhance the performance of standard gloves and improve joint posture accuracy. State-of-the-art kinematic modeling, incorporating additional potentiometers, has dramatically enhanced angle accuracy, particularly in PIP joints. This significantly impacts rehabilitation, enabling more accurate detection of motor intention and feedback in subtle hand movements [17].

To further improve dexterity, low-weight vibrotactile haptic gloves with virtual reality games embedded within them have been developed. The systems provide finger-selective vibration feedback to teach user movement, improving response time and motor activation. Their modular, low-cost design allows for flexibility between hand sizes, making it possible to use them in both clinic and home environments [18].

Whole-hand haptic devices have also emerged, integrating end-effector robots and glove modules to offer virtual object grasp simulations. The devices allow for proportional haptic rendering, real-time feedback control, and high usability. Clinical trials suggest their potential for improving Activities of Daily Living (ADL) skills and enhancing motor-sensory integration [19].

Simpler glove systems, utilizing flex sensors and vibration motors with Arduino control, have effectively motivated patients through real-time interaction and tactile feedback. Although thumb tracking and multi-modal feedback are limited, they offer a trade-off between cost, usability, and therapeutic impact [20].

Research conducted through meta-analysis demonstrates that patients benefit most from using a haptic glove in semi-immersive VR to develop upper limb motor function through integrated conventional therapy. When used in conjunction with more comprehensive rehabilitation programs, glove-VR devices enhance motor performance and coordination, with their long-term effects being particularly potent [21].

The authors endorse using haptic connection and tactile stimulation during modern rehabilitation practices and emphasize the need for haptic interface technology to restore hand functionality.

Soft Robotics & Sensor-Based Actuation 2.8

Focus: Smart textiles, passive/soft actuation, FMG sensors

Soft robotics and sensor-actuated actuation gradually assume forefront roles in rehabilitation technology development, offering flexibility, wearability, and a natural user interface. Such systems are inclined to integrate compliant mechanisms and multimodal feedback to facilitate enhanced motor recovery, but at the cost of comfort and portability.

Fabric-based haptic devices, such as electro-adhesive sleeves, represent a departure from conventional rigid robots. By delivering kinesthetic error feedback during motor tasks, lightweight devices can facilitate improved acquisition and maintenance of skills without adding mechanical sophistication. For virtual tasks, haptic sleeves reduced baseline errors by over 37%, supporting their suitability for neuromotor rehabilitation of joints such as the elbow and wrist [22].

The CUFF device provides supplementary tactile feedback through its combination of skin-stretch technologies and compression functions, which are achieved with textile belts that DC motors activate. Users demonstrated precise force discrimination in psychophysical tests, enhancing their ability to recognize objects and improving their body posture during manipulation. The platform assesses the potential of complex tactile feedback technology for both teleoperation systems and rehabilitation applications [23].

Furthermore, clinical applications benefit from devices similar to the VTS Glove, which delivers passive vibrotactile stimulation through the glove to decrease spasticity and improve tactile sensitivity in stroke patients. The glove demonstrated significant improvements in motion capabilities and sensitivity perception following eight weeks of self-use, even among individuals who did not wear it, indicating positive effects of unpowered stimulation [24].

From a usability perspective, soft systems must also be tested for cognitive load and accessibility. Reviews recommend using standardized usability metrics, such as the System Usability Scale (SUS) and NASA-TLX, while promoting hybrid evaluations that combine subjective responses with physiological ratings to enhance design outcomes [27].

The E-Glove is a low-cost, interactive wrist rehabilitation system that uses accelerometry and vibro-feedback in a game-based environment. As a home-based system, it couples user interaction with therapy goals, allowing ROM monitoring and motivational stimuli for post-stroke rehabilitation [29].

These innovations establish soft robotics as a versatile and user-friendly pathway toward more inclusive and effective rehabilitation.

Advanced Sensing & Machine Learning 2.9

Focus: Sensor-driven AI models, hybrid signals, control optimization

The intersection of machine learning algorithms with sensing technologies is transforming rehabilitation robotics via enhanced diagnostic precision, personalization, and predictive control. Wrist-worn and motion-tracking sensors, as an essential part of exoskeleton-assisted therapy, have gained increasing interest from the academic community in the applications of motor disorder treatment [4, 5, 7].

Real-world monitoring using accelerometers and IMUs has enabled the subtle assessment of motor deficits in stroke and ataxia-telangiectasia (A-T) patients. These systems capture sub movement differences, motion asymmetry, and functional changes that standard clinical scales may not capture. For example, studies with week-long wrist monitoring in A-T patients showed strong correlations with clinical assessment instruments and enabled the detection of disease progression very early. Similarly, in rehabilitation from stroke, 24/7 accelerometer monitoring demonstrated impressive motion improvement not monitored by conventional evaluations like the Motor Assessment Scale (MAS) [4, 5].

Capacitance sensing and motion variability analysis have also been examined in Parkinson's Disease, with the patients presenting with reduced wrist coordination and flexibility. Variability parameters acquired from the sensor, especially on the wrist extension, provided high sensitivity in detecting motor rigidity and, therefore, deserve their use in monitoring therapy and early detection [7].

Wearable pressure sensors such as laser-induced graphene (LIG) insoles push the boundaries of real-time gait identification and exoskeleton phase control. In rehabilitation, SVM-based classifiers using LIG sensor information achieved 99.85% accuracy in the gait phase detection. Such systems allow precise robotic actuation synchronized with user motion, enabling safe and dynamic patient-exoskeleton interaction [34].

Sensor fusion with EMG, EEG, and kinematics remains in the spotlight at the systems level. Overviews emphasize adaptive control, especially impedance, and assist-as-needed control approaches to attain optimal rehabilitation performance. Designed initially for the lower limb, these frameworks now directly inform upper-limb and wrist devices and promote real-time, user-adaptive, portable designs [36].

Multiple studies demonstrate how machine learning technology enables rehabilitation systems to become more data-driven, patient-focused, and responsive healthcare solutions.

Conclusion of the Background Research 2.10

Briefly, existing wrist-rehabilitation devices trade high-torque, rigid linkages and safer implementations at the expense of friction, reduced DOFs, or compromised wearable comfort. Sensor fusion, fusing surface EMG, force/torque sensing, and IMUs, permits intent-driven, assist-as-needed control but requires careful calibration and filtering to manage noise and drift. Advanced control strategies like impedance/admittance and machine-learning-based intention detection have shown improved engagement over passive trajectories. Yet, no system has thus far combined active assistance with passive guidance seamlessly. Bilateral mirroring and real-time feedback also enhance neuroplasticity but are challenged by muscle fatigue and stability during prolonged sessions. Above all, no device yet merges anatomically aligned, low-friction mechanics, multi-modal sensing, and hybrid control in an easy-to-use, home-usable form factor. Our work bridges this gap by incorporating a curved rack-and-pinion transmission, real-time sensor fusion, and seamless active–passive switching in a lightweight, ergonomic exoskeleton.

Table 1: Background Review

Aspect	What Exists	Unmet Needs	Our Focus
Sensors	EMG-only, IMU, F/T separately	Complete multimodal fusion, real-time calibration	EMG + F/T + encoder fusion
Control	Passive/active only, fixed gain	Adaptive AAN, fatigue compensation	Hybrid active–passive, ML-ready
Mechanics	Cable drives, limited ROM, high friction	Low-backlash, anatomical alignment, and low inertia	Curved rack-pinion, COM-balanced
Usability	Bulky, complex donning	Lightweight, quick setup, high comfort	Ergonomic one-handed design

Chapter 3: Scope of Innovation and Objectives

The literature about wrist rehabilitation devices detects multiple limitations that researchers should address to achieve better results in device performance and medical functionality. Different challenges exist in wrist rehabilitation devices, which cluster under four main categories: device mechanics, sensor technology, adaptive control development, and comfort of user experience. Our project targets these innovation aspects for development:

Sensor Integration and Real-Time Feedback 3.1

Challenge Identified: Real-time adaptive sensor feedback remains essential for personalized rehabilitation, yet most current wrist exoskeleton models do not provide these features because they lack the necessary sensor integration. Current designs featuring force/torque sensors and EMG sensors, as well as other sensor systems, rarely receive full integration since these components remain either underutilized or absent, which prevents adaptive real-time assistance for the patient.

Aim: The proposed system implements force and torque sensor devices onto the OpenWrist system to deploy adaptive control protocols. The system employs force sensors that adjust resistance dynamically according to patient needs through surface electromyography (sEMG) muscle force measurement. The joined features enable customized rehabilitation assistance. Through its new features, the system will enhance its ability to adapt dynamic feedback and adjust patient physical profile capability in real-time.

Active and Passive Control Mechanisms 3.2

Challenge Identified: Current robotic systems operate with a single control system that is either robot-operated (active) or controlled by the user(passive). The inability of passive-only exoskeletons to sufficiently engage rehabilitation patients diminishes their effectiveness as treatment tools for extended periods. Others with active control systems are less adaptable to patient feedback.

Aim: A hybrid control system emerges through our project due to its integration of active control elements with passive assist features that enable patient active participation. Our system has adaptive capabilities that will adapt to patient needs by automatically adjusting support levels during assist-as-needed rehabilitation. A system adaptation technique will enhance motor recovery because the device will adapt to evolving patient ability levels and recovery needs.

Ergonomics and Usability 3.3

Challenge Identified: Exoskeleton devices for the wrist tend to be bulky, uncomfortable, and challenging to use because of their installation and removal requirements, which pose difficulties for those with motor function limitations. Some of them offer better ergonomic solutions yet require additional improvements in comfort alongside ease of use, primarily for extensive rehabilitation environments.

Aim: The device's comfort improves for extended periods of use by implementing flexible structures, lightweight materials, and user-based adjustments. The equipment effectively treats patients by offering washable and removable parts such as the liner and adjustable straps, which improve patient adherence and maximize therapeutic outcomes in-home therapy. These new features allow medical equipment to treat patients effectively using home therapy.

Intelligent Control Strategies 3.4

Challenge Identified: Most current exoskeletons do not possess adaptive control systems that can adjust their responses based on the user's changing levels of participation and applied strength during use. The current control systems only implement basic mechanisms that do not use real-time feedback algorithms for improved patient interactions.

Aim: Our project harnesses real-time feedback to modify resistance and movement trajectory in real time during patient interactions. Comparing data patterns to fatigue indicators and muscle activation data will enable developers to set up individualized adaptive rehabilitation strategies. Feedback loops could be a system component to ensure the highest therapy outcomes by adapting to optimize rehabilitation targets.

Chapter 4: Methodology

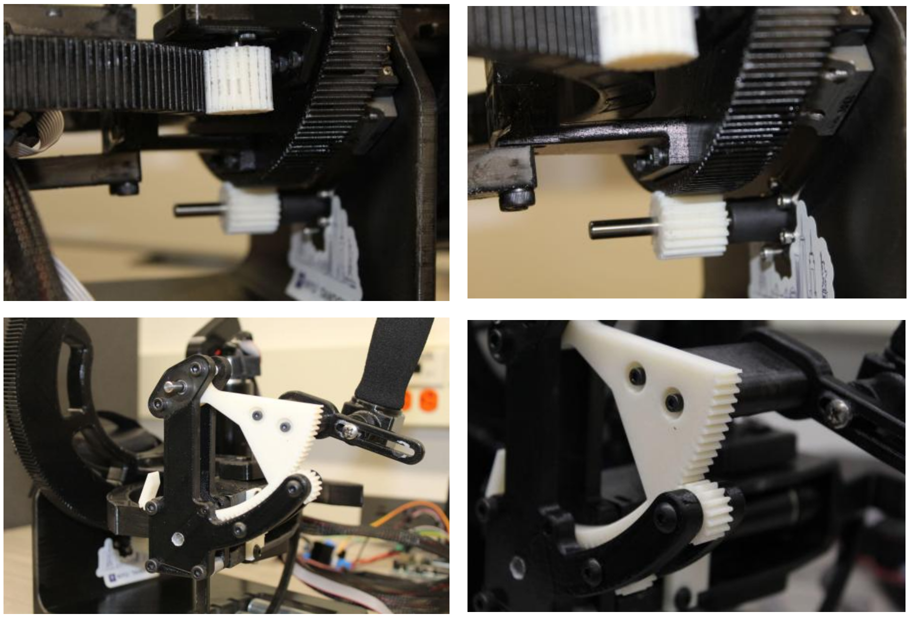
The Wrist Rehabilitation Exoskeleton for wrist motor rehabilitation follows an organized development process that targets developing an ergonomically optimized, high-performing, adjustable device. The development adopts knowledge of patient-specific wrist impairment needs, especially for stroke survivors who need wrist motor recovery. A systematic approach for developing the Wrist Rehabilitation Exoskeleton uses a sequence that begins with conceptual design and mechanical optimization, after which sensory feedback systems and control algorithms are integrated. The fabrication and assembly of the prototype involve executing work to create a user-friendly product that remains durable and provides comfort for long-term use. The researcher performed a complete set of tests to measure exoskeleton mechanical abilities, sensor connections, and patient interface standards so the device could meet patients' therapeutic requirements. The following sections in the development process diagnose specific stages that introduce innovative features into the exoskeleton system for personalized, adaptive, and effective wrist rehabilitation delivery.

Design and Development of the Wrist Rehabilitation Exoskeleton 4.1

The Wrist Rehabilitation Exoskeleton has been built to improve its mechanical capabilities and user-friendly experiences when treating motor impairment through rehabilitation. The project resolves several problems in existing products, along with torque efficiency, range of motion (ROM) restrictions, and friction affecting performance. The system design combines a gear and a curved rack-and-pinion system to eliminate the conventional capstan-cable transmission process and reduce the mechanism's frequent wear and tear. The project team implemented this solution to fulfill multiple essential design targets, including precision enhancement, torque boost, friction reduction, and inertia minimization.

Mechanism Design 4.1.1

I preferred the gear and rack-pinion mechanism to the capstan-cable mechanism to enable direct torque transmission as well as high precision levels with minimized backlash. Force transmission using the capstan-cable system remains operational but introduces system complexity and non-linear torque responses that can decrease precision and accelerate equipment wear. The rack and pinion mechanism creates a direct mathematical correlation between rotational motions and force application, thereby providing precise, predictable, responsive motion, which rehabilitation robots need to restore motor functions.



Figures 1, 2, 3, 4: Curved Rack and Pinion

The wrist exoskeleton mechanism consists of gears combined with a curved rack that was designed to mimic the natural movements of the wrist between the PS, FE, and RU joints. The specific geometry of the curved rack enables the transmission system to follow naturally with the movement of the user's wrist and avoid unwanted pressure on their wrist joints. Combining the newest gears provided less friction than earlier gear combinations, making smoother movements and varying along the device's length. The reliability of repetitive motion rehabilitation devices relies on their ability to withstand repeated use without failure to function.

Mechanical Performance and Range of Motion (ROM) 4.1.2

The device obtained its expanded range of motion (ROM) through the gear and rack-pinion system combination. The adjustable and adaptable structure in the mechanism enables the wrist exoskeleton device to surpass the standard movement range limits found in most rehabilitation systems. Our rack and pinion system's long, rational adjustment work produced extension and flexion motion extending up to 150° along with pronation and supination motion reaching 180°, which precisely duplicates standard wrist motion. Patients who undergo neurological recovery benefit significantly from total active ROM because it enhances functional daily activity execution capabilities.

Table 2: Wrist ROM measurements in healthy people and the ROM measured in the exoskeleton construction.

Movemet	**Normal ROM (Healthy Individual)**	**Achieved ROM (Exoskeleton)**
Flexion/Extension (FE)	±80° to ±90°	±175°
Pronation/Supination (PS)	±80° to ±90°	±190°
Radial/Ulnar Deviation (RU)	±15° to ±25°	±90°

This increased range of motion has significant therapeutic advantages, enabling more thorough rehabilitation training and encouraging recovery for a greater range of wrist tasks.

Friction Reduction and Inertia Minimization 4.1.3

Compared to the capstan-cable and another mechanical system, the gear and curved rack-pinion mechanism is stronger due to its capability to minimize inertia and friction, which determines the wrist rehabilitation device's effectiveness. High friction losses occur in the capstan-cable system because multiple bends alongside frictional surfaces on the cable system lead to increased mechanical wear and reduced system longevity. A direct drive system within the gear and rack-pinion mechanism enhances power transmission efficiency and reduces friction-based obstacles.

The smooth performance of rehabilitative exercises and the user comfort required for extended usage in clinical and home settings are directly impacted by the mechanical efficiency attained by these advancements.

User-Centric Design and Ergonomics 4.1.4

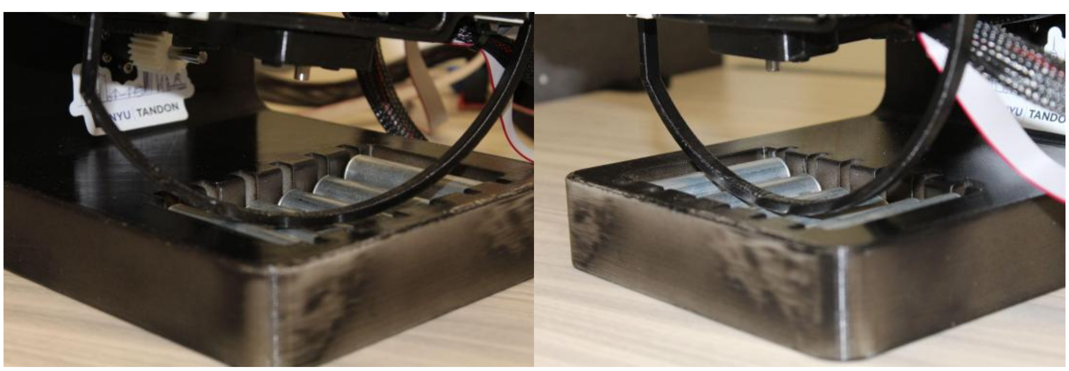
This exoskeleton meets varied user requirements because of the modular frame, which integrates with adjustable handgrips to enable easy fitting and accommodate use with the left and right hands. The open framework design provides users with ease of application convenience. It supports diverse user capabilities, like reduced skin elasticity and restricted range of motion, to solve conventional usability problems in previous designs.

Summary of Design Innovation 4.1.5

This wrist rehabilitation exoskeleton relies on a curved rack-pinion mechanism and a gear mechanism, which is more functional than other traditional devices. The system provides more precise movement with more torque power, limits friction, and maximizes the range of motion capacity and mechanical system efficiency. Designed through a user-centric approach and its innovative features, this exoskeleton becomes a superior and more comfortable tool for wrist rehabilitation programs. This research demonstrates essential progress in wearable rehabilitation tool design because it provides a system with technical excellence and easy-to-use capabilities.

Optimization of Center of Mass for Enhanced Friction Reduction and Improved Motion Efficiency 4.1.6

Initially, the center of mass (COM) was positioned in the front portion of the Wrist Rehabilitation Exoskeleton design. The placement of this center of mass created exaggerated friction within the Pronation/Supination (PS) joint because improper weight balance made the load transfer inefficient, thus producing excessive resistance when performing movement. The developed friction reduced the smoothness and responsiveness of the exoskeleton, particularly when performing wrist rotations. Adding a rotating support structure transferred the center of mass for better balance, thus addressing the technical issue. Structural alteration eradicated the excess friction at the PS joint, smoothing the overall device motion. COM optimization improved torque transmission and the system's ROM performance. The device quality rose through improved balance because it decreased mechanical resistance while improving user comfort and device compatibility with extended rehabilitation sessions. The introduction of this innovation enables better adaptive wrist motions, which improves rehabilitation performance.



Figures 5,6: Rotating Support

Sensor Integration and Feedback System 4.2

The integration of high-level sensors is critical to both the operation and flexibility of the Wrist Rehabilitation Exoskeleton. These sensors provide real-time feedback to enable the device to respond dynamically to the user's physical condition, providing personalized assistance during rehabilitation exercises. This subsection discusses the integration of three main sensors: electromyography (EMG) sensors, force/torque sensors, and optical encoders, each playing a crucial role in delivering adaptive feedback and the overall rehabilitation exercise.

Sensor Selection and Placement 4.2.1

The system integrates three distinct types of sensors:

1. **EMG Sensors:** The sensors evaluate electrical muscular signals to determine active muscle contractions and their activation behaviors across tasks. The user interfaces with haptic glove devices equipped with EMG sensors placed to detect muscle contractions. During user-handled rehabilitation exercises, the haptic glove interprets hand and wrist muscle movement data through its reading capabilities. The gathered information becomes useful to control the exoskeleton's response by adapting user-specific support according to individual muscle activation signals.
2. **Force/Torque Sensors:** The haptic glove integrates force and torque sensors, just like its EMG sensors. These sensors measure the force exerted by the user during wrist motions and thus provide data on exerted effort and joint resistance. With constant and simultaneous measurement of these forces, the system allows for adaptive feedback to adjust torque output and exoskeleton resistance, ensuring that the device provides sufficient assistance specific to the user, which subsequently results in improved functional recovery and comfort.
3. **Optical Encoders:** The optical encoders are mounted on the motor shafts, which enable tracking of the device's rotation. The encoders track continuous ROM to verify that the device stays within the designed range while maintaining correct positioning. The exoskeleton requires optical encoder data to operate in closed-loop control due to its ability to automatically adjust movements accurately, thus delivering precise and controlled motions.

Sensor Fusion and Adaptive Feedback 4.2.2

Data collected from EMG, force/torque, and optical encoders are integrated and processed in the exoskeleton control system. In integration, the system responds instantaneously to the physical need and state of the user. It provides dynamic support in terms of the involvement and the user's effort level. For example, the system can modulate the resistance according to the force/torque feedback of the glove, along with changing its motion response according to the muscle activation feedback of the EMG sensors.

The sensor fusion mechanism provides the exoskeleton with the optimal response, providing the correct level of support or assistance depending on muscle fatigue, motion intention, and the individual's rehabilitation needs. The system also employs the feedback loops of the optical encoders to regulate the rotational speed and direction of the motor to provide proper wrist movement and maintain appropriate ROM during rehabilitation.

Challenges and Future Enhancements in Sensor Integration 4.2.3

While the sensor integration system is designed to provide adaptive and personalized feedback, there are still challenges in sensor calibration, noise in the signal, and haptic glove-exoskeleton integration. For example, sustaining the force/torque sensors on the glove and accurately measuring the user's grip strength without adding noise and error needs to be developed. Moreover, the system should allow real-time data exchange between glove and exoskeleton sensors so that no time delay is introduced. As an extension of research along this line, the upcoming research will include calibrating sensor fusion algorithms to improve further fusion of EMG, force/torque, and encoder signals, and exploration of advanced machine learning algorithms for optimizing adaptive control based on user performance.

Control Systems and Algorithms 4.3

The exoskeleton's control architecture delivers responsive, biofeedback-regulated actuation through the integration of precise motor control with real-time sensor information. It is centered on Maxon's EPOS4 motor driver, controlled through Python via the EPOS Command Library (EposCmd64.dll). Motor control logic is encapsulated within a Python interface specially created for this task, prosthesis.py, which communicates with the EPOS4 through dynamic linking and a .NET wrapper.

A Motor class in modular form sets basic control parameters - direction, angle, torque, acceleration, and encoder values, in which dynamic control can be executed by either Profile Position Mode (PPM) or Current Mode (CM). Angle and torque as user input are recorded per movement cycle, where they are scaled individually for PS, RU, and FE joints to provide varying torque and range of movement requirements. Commands are paralleled with VcsWaitForTargetReached, and telemetry data such as actual position, velocity, and encoder values are recorded per actuation.

The system's central controller is a Raspberry Pi 5, which performs the function of a communication bridge and a real-time decision-making unit. The Pi is interfaced with two biofeedback sensors: a Flex Sensor and an EMG sensor. The Flex Sensor, mounted at the

joint on the haptic glove, provides torque output exerted by the user to detect mechanical deformation. In contrast, the EMG sensor detects electrical muscle activation signals. These inputs enable the system to make real-time estimates of user intent and resistance.
Straightforward feedback loop enables adaptive action: during low EMG values or high flex sensor readings (which correspond to resistance or fatigue), the control algorithm can relax motor torque or delay initiating motion, replicating a rudimentary Assist-As-Needed (AAN) strategy. While initial control logic relies on rules, the design does include machine learning-based models for trajectory following and adaptive impedance down the line.
Adding telemetry reporting, fault management, and safety features like motion range protection ensures user reliability and safety. The system's scalability, low latency, and modular design make it an ideal starting point for complex rehabilitation control algorithms, combining cost-effective open-source platforms with industrial-level actuation accuracy.

Prototype Development and Fabrication 4.4

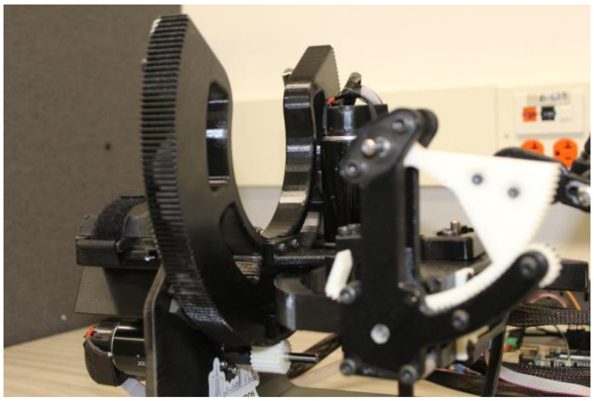
Fabricating the Wrist Rehabilitation Exoskeleton prototype is fundamental because it enables the development of an exoskeleton that fulfills functional needs and mechanical capabilities while providing durability alongside comfort and usage. Production of the Wrist Rehabilitation Exoskeleton involved high-durability ABS (Acrylonitrile Butadiene Styrene) materials, which establish themselves through their capacity to resist mechanical pressure and ensure rigidity and strength. The selection of ABS material worked well for rapid prototyping and serial components production because it provides strong mechanical properties at an affordable price.

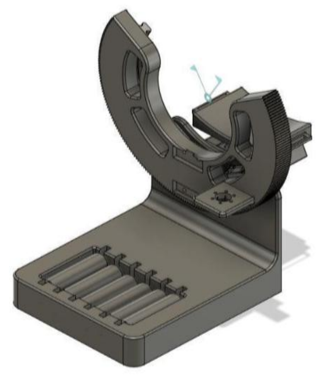
Material Selection 4.4.1

Using ABS in all exoskeleton parts ensures the system has high strength-to-weight ratios without compromising durability. For maximum structural strength, different infill parameters were applied for various components of the exoskeleton. The frame, joints, and actuation units that form the load-carrying components were printed using high-density infill to supply the highest level of strength and resistance. Such elements are subjected to high forces and stresses when installed, and, as such, it is very critical to maximize their structural reliability without adding unnecessary weight.
At the same time, non-load-bearing structures, such as connectors and housings, were produced using lower-density infill, reducing the weight of the entire device without sacrificing the strength and durability required for long-term use. With selective infill, the exoskeleton is kept as light and ergonomic as necessary, essential for patient comfort during prolonged rehabilitation sessions.

3D Printing Process 4.4.2

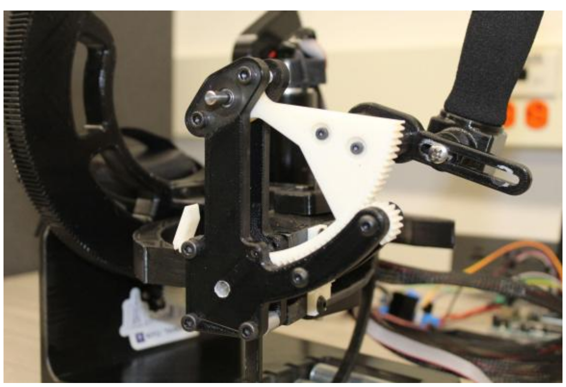
The 3D printing technology enabled a quick prototyping process while simultaneously making it possible to validate parts design changes before assembling the final product. Each part was carefully designed in CAD software and then printed using Fused Deposition Modeling (FDM) into ABS-based prototypes using their popular 3D printing technology. FDM was selected because it can produce high-quality, strong, and dimensionally correct parts at a reasonable cost.

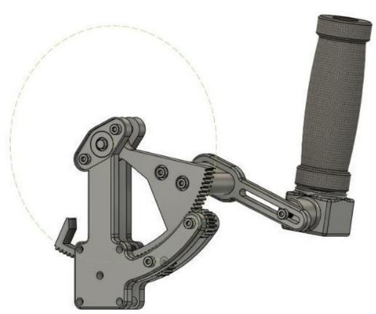




Figures 7,8: Load Bearing Parts

For load-bearing parts, the printing settings were optimized to provide high infill densities, generally in the range of 70%-100%, depending on the individual part's need for stress. The flexion/extension joints and pronation/supination joints, subject to high stresses through the rehabilitation exercises, were given increased infill to support repeated stresses and ensure long-term functionality. For parts such as the hand grips or sensor mounts, lower infill densities (generally in the range of 20%-40%) were used, reducing weight without compromising overall strength.

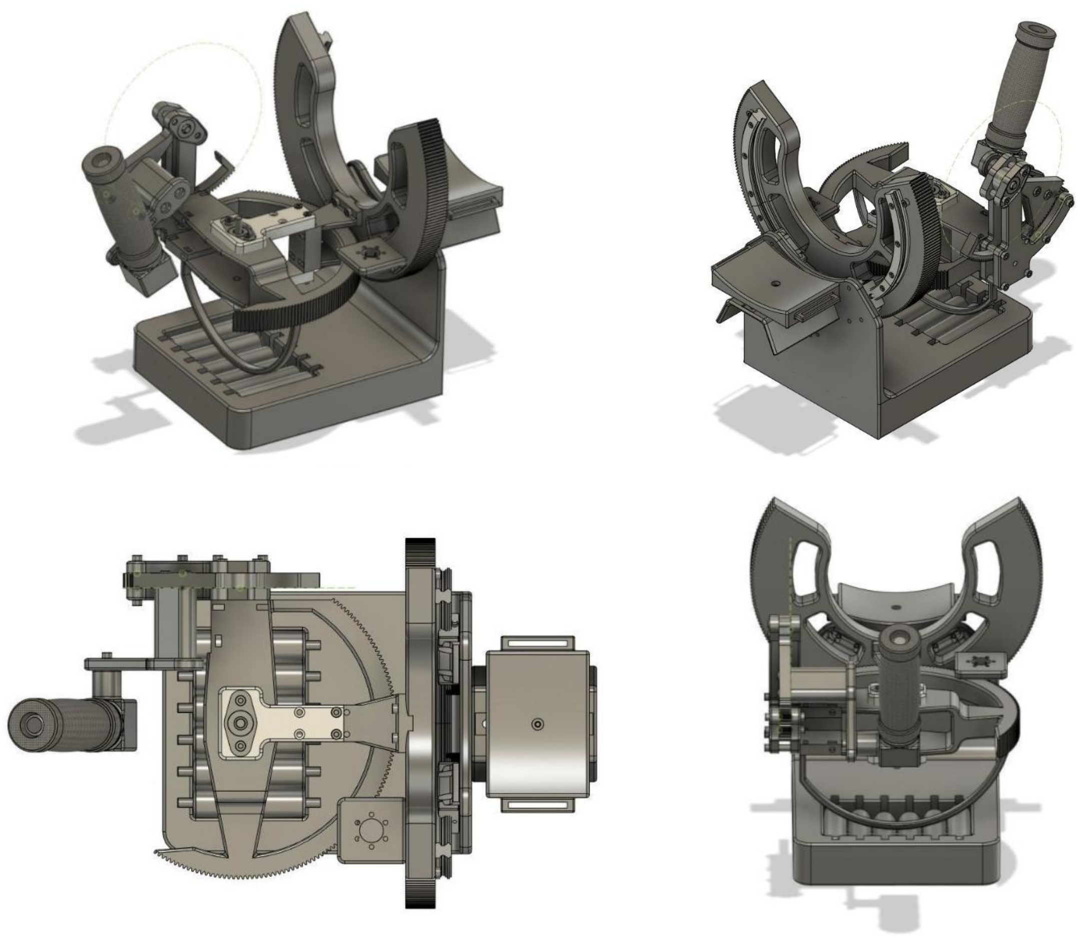




Figures 9,10: Non-Load Bearing Parts

Assembly Process 4.4.3

Electric wiring was carefully placed to prevent interaction with the system's moving elements. Internal frame cavities served as the wiring integration spaces, maintaining external structural cleanliness without any hindering obstructions. The final assembly included integrating the haptic glove and both EMG sensors, along with the force/torque sensors, to establish seamless communication between the glove and the exoskeleton.
I designed the electrical wiring with precision to prevent moving components and external elements from interfering with the system. The frame's internal cavities received the cables as part of the cabling design, maintaining an exterior space without obstructing elements. EMG sensors and force/torque sensors on the Haptic glove were integrated with the final assembly design to achieve communication between the glove and exoskeleton.



Figures 11, 12, 13, 14: Wrist Rehabilitation Exoskeleton

Testing and Evaluation 4.5

The success of the Wrist Rehabilitation Exoskeleton relies on its ability to offer effective rehabilitation and be mechanically stable and easy to use. This subsection explains the testing procedures and evaluation criteria used to ensure the performance of the exoskeleton in relation to range of motion (ROM), sensor accuracy, user comfort, and system reliability. The experiments were performed to assess both the mechanical performance of the device and the adaptive feedback system, which provides real-time, personalized rehabilitation.

Mechanical Performance Testing 4.5.1

One of the primary objectives of the testing procedure was to ensure that the Wrist Rehabilitation Exoskeleton met the required range of motion (ROM) for each of the three primary wrist movements: flexion/extension (FE), pronation/supination (PS), and radial/ulnar deviation (RU). The ROM of the exoskeleton was evaluated through the use of a positioning system with optical encoders attached to the motor shaft. The readings from the optical encoders allowed the control system to modify the joint positions in real time with feedback so that the wrist motion closely approximates the natural ROM of a healthy wrist.

Table 3 ROM from Healthy Individual vs Achieved

Movement	Normal ROM (Healthy Individual)	Achieved ROM (Exoskeleton)
Flexion/Extension (FE)	±80° to ±90°	±150°
Pronation/Supination (PS)	±80° to ±90°	±180°
Radial/Ulnar Deviation (RU)	±15° to ±25°	±90°

The ROM values recorded exceed the minimum ROM for activities of daily living (ADLs) to guarantee that the exoskeleton can effectively support a range of functional movements necessary for rehabilitation.

Sensor Performance and Calibration 4.5.2

The real-time adjustment of the exoskeleton relies significantly on precise and uniform sensor readings. Therefore, thorough testing was conducted to examine the performance of the force/torque and EMG sensors implemented in the haptic glove. The force/torque sensors were calibrated by evaluating the forces applied by several test subjects for controlled wrist movement. The device measured sensor outputs against preset values for an accuracy check, followed by testing how real-time control of the motor resistance functioned.
Likewise, the EMG sensors were calibrated to respond to muscle activity with wrist movement. Using various force and muscle activation levels, the system was tested to see whether the adaptive feedback system would be sensitive to varying muscle activation levels. The sensor fusion algorithm, combining data from all three sensors, was tested to see whether proper integration and real-time compensation were being made.

User Comfort and Usability Testing 4.5.3

Comfort and ease of use for the user take precedence in the design of rehabilitation devices that are to be worn over long durations. In order to establish the ergonomic design of the exoskeleton, a series of user trials were conducted on healthy participants. Feedback was received on comfort, ease of use, and adjustability. Participants wore the exoskeleton for varying durations and performed a series of rehabilitation exercises designed to mimic common activities of daily living.
Apart from subjective observations, force measurements and joint movements were used to ensure that the device would be comfortable and impose no undue stress on the subject. Weight, fit, and adjustability were the most important factors that were tested, ensuring that the device was appropriate for short-term treatment as well as prolonged rehabilitation therapy.

System Reliability and Durability Testing 4.5.4

Finally, the durability and reliability of the device were confirmed with stress testing of the exoskeleton in simulated rehabilitation settings. The device was subjected to extended use trials in which it was worn for several hours a day over the course of weeks to evaluate its performance in the long term. Mechanical wear on the actuators, sensors, and joints was monitored to ensure that these elements would be capable of withstanding the stresses of repeated use without experiencing any appreciable degradation of performance.
These tests' outcomes demonstrated that the exoskeleton could continue to work reliably for prolonged periods without experiencing any serious mechanical or sensor issues.

Limitations and Challenges 4.6

While design and development of the Wrist Rehabilitation Exoskeleton have become considerably better in mechanical design, sensor integration, and overall system performance, there are still some limitations and challenges that need to be addressed in subsequent versions of the system to continue to enhance its functionality, reliability, and clinical effectiveness. This subsection documents the principal challenges encountered through design and test activities and the limitations of the existing prototype.

Sensor Calibration and Accuracy 4.6.1

One of the most significant challenges faced in the exoskeleton design is the sensor calibration process. The EMG sensors, force/torque sensors, and the optical encoders were calibrated to ensure that every sensor accurately measures the respective parameters, i.e., muscle activation, force applied, and joint position. Minor calibration errors can lead to deceptive sensor readings, which will, in turn, negatively affect the system's adaptive feedback and real-time response.

To resolve these calibration issues, each type of sensor was manually baseline calibrated. EMG thresholds were set up from relaxed and contracted muscle and force sensors by known weights. Optical encoders were zeroed in the neutral wrist position and tested for accuracy through full ROM. This allowed for precise sensor output for robust real-time feedback using individual patient measurement data.

Power Efficiency 4.6.2

Although the exoskeleton's design is optimized for performance, power consumption was a big challenge, especially for users who need to wear the device for extended periods. A rechargeable battery powered the prototype, but the power consumption of the actuators and sensors limits the total operational time between charges. Longer battery life was essential in keeping the device usable within clinical and domestic settings, in which users would likely need to wear it for several hours at a time.

To address this issue, we removed the battery from the system and inserted an electronic adapter that converted the 220V AC directly to 20V DC for the Exoskeleton. This ultimately solved the problem of the short charge time.

Sensor Noise and Signal Interference 4.6.3

Listed sensors, including electronic muscle signal detectors (EMG) alongside force/torque sensors, bring challenges since their combined signals tend to generate data inaccuracies in adaptive control systems. EMG signals experience interference from external electrical sources at the same time that force sensors show sensitivity to mechanical vibrations from motor operations. The feedback accuracy suffers when sensors are interfered with, thus preventing the system's real-time adaptability.
EMG wires were shielded and positioned away from motor wiring to minimize electrical crosstalk and signal noise. These actions maintained the accuracy of real-time feedback while enhancing signal stability.

Durability and Long-Term Use 4.6.4

The ABS materials used for the exoskeleton structure meet weight-to-strength requirements but pose problems with developing durability issues during continuous use because of stress and friction accumulation compared to other materials. Exoskeleton components, consisting of joint gears and cables, undergo deterioration from regular usage since their exposure to wear and tear results in eventual mechanical breakdown during extended operation.
Better durability performance can be achieved by evaluating high-performance composites and metal alloys as materials for vital load-bearing elements. Lubrication systems paired with maintenance-free bearings would fight friction and reduce wear on moving parts.

Clinical and Real-World Testing 4.6.5

The ultimate proof of the Wrist Rehabilitation Exoskeleton lies in its effectiveness in performing effective rehabilitation in real clinical and domestic settings. While the system has been tested on healthy volunteers, it must undergo rigorous testing on patients with wrist impairment due to stroke or Parkinson's disease. Clinical trials are needed to validate the therapeutic capability of the device and its ability to meet specific patient needs in the rehabilitation process. Clinical trials will be carried out on at least 30 patients, and an IRB will be submitted for approval before conducting the study.

The work approach included in this thesis outlines an effective approach to Wrist Rehabilitation Exoskeleton design, manufacturing, and testing. Key innovations, such as the use of a gear and curved rack-pinion mechanism for joint articulation and integration of sensor feedback systems (EMG, force/torque sensors, and optical encoders), are central to enhancing the device's performance and responsiveness in real-time rehabilitation.

Mechanical design was optimised to yield the maximum ROM and reduce inertia and friction, which are crucial for optimising user comfort and device sensitivity. The design decision to install a rotating bearing system to achieve maximal COM was effective in reducing the friction, primarily at the pronation/supination (PS) joint, to provide smoother as well as non-resistance movement. The high-durability ABS material, as well as selective infill approaches, were chosen in an attempt to achieve the best strength, weight, and durability balance.

Real-time muscle activity, together with wrist movement detectable through sensor integration, allows the device to modify its resistance and torque levels. The precise control systems obtain their accurate capabilities through the data combination of EMG sensors with force/torque sensors and optical encoders to provide individualized therapeutic solutions.

However, there remain challenges with sensor calibration, power efficiency, and adjustability specific to each user. Therapeutic benefits as well as real-world effectiveness of the exoskeleton require clinical trials combined with prolonged testing procedures.

The methodology establishes a solid approach for developing the Wrist Rehabilitation Exoskeleton to function as a patient-focused rehabilitation device that helps patients to recover wrist strength and functionality in comparison with healthy individuals.

Chapter 5: Mechanical Design and Specifications

This chapter thoroughly describes the wrist rehabilitation exoskeleton's mechanical design features. It contains 2D technical drawings depicting major components together with dimensional annotations.

The technical drawings represent the dimensions utilized for manufacturing the exoskeleton during its physical fabrication process.

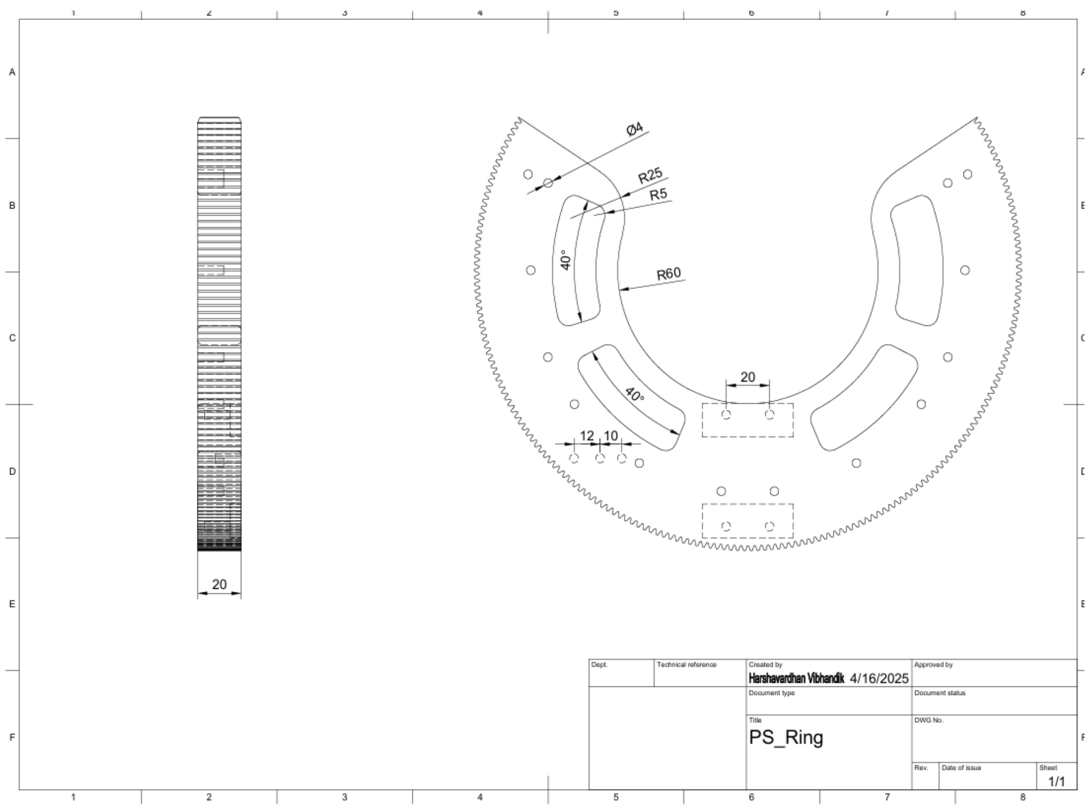


Figure 15: PS Ring

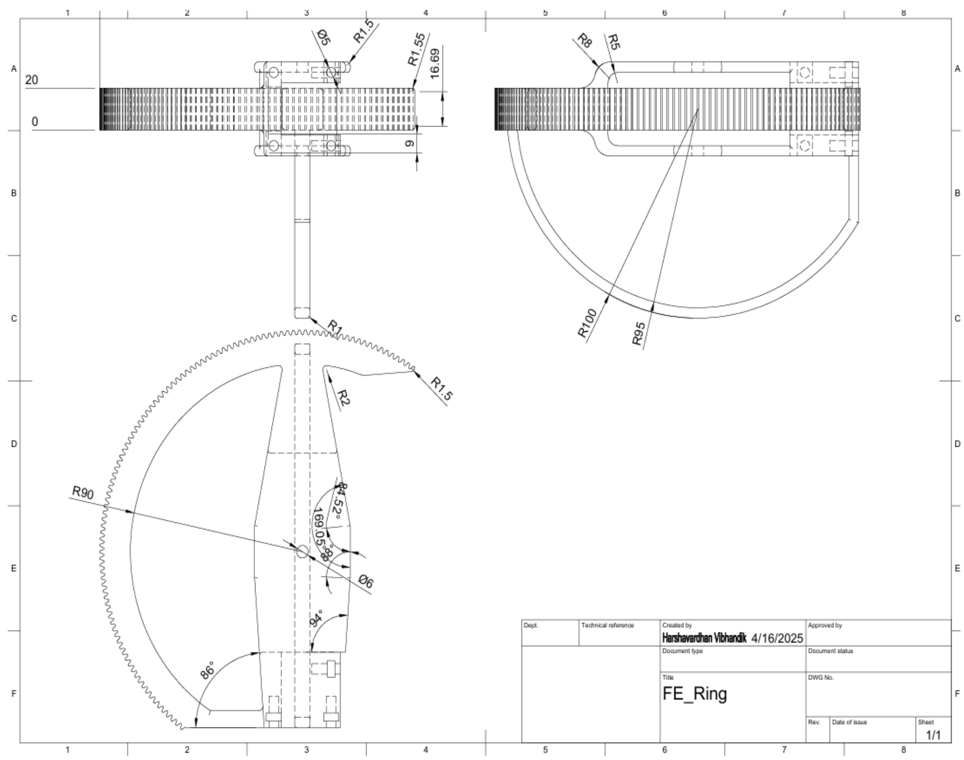


Figure 16: FE Ring

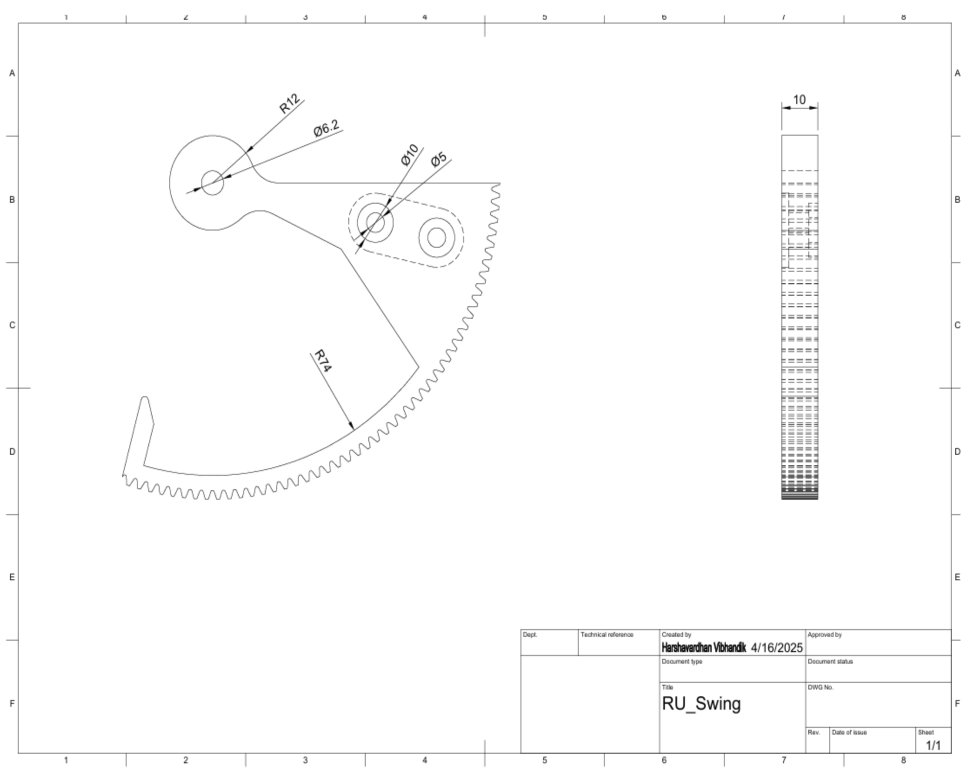


Figure 17: RU Ring

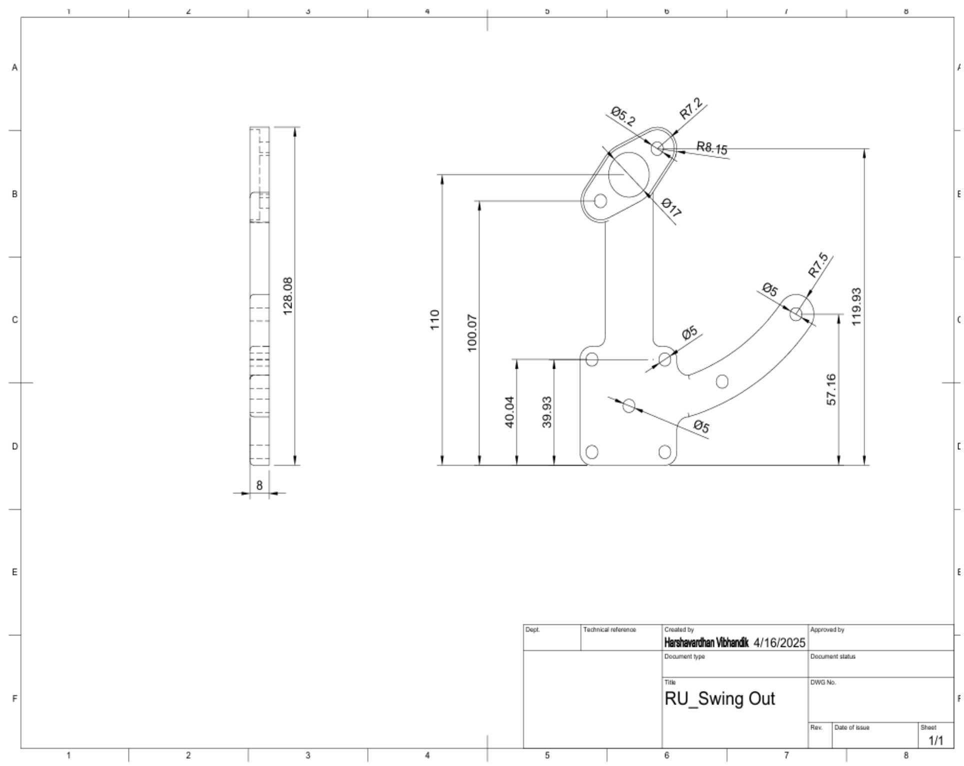


Figure 18: RU Ring Holder 1

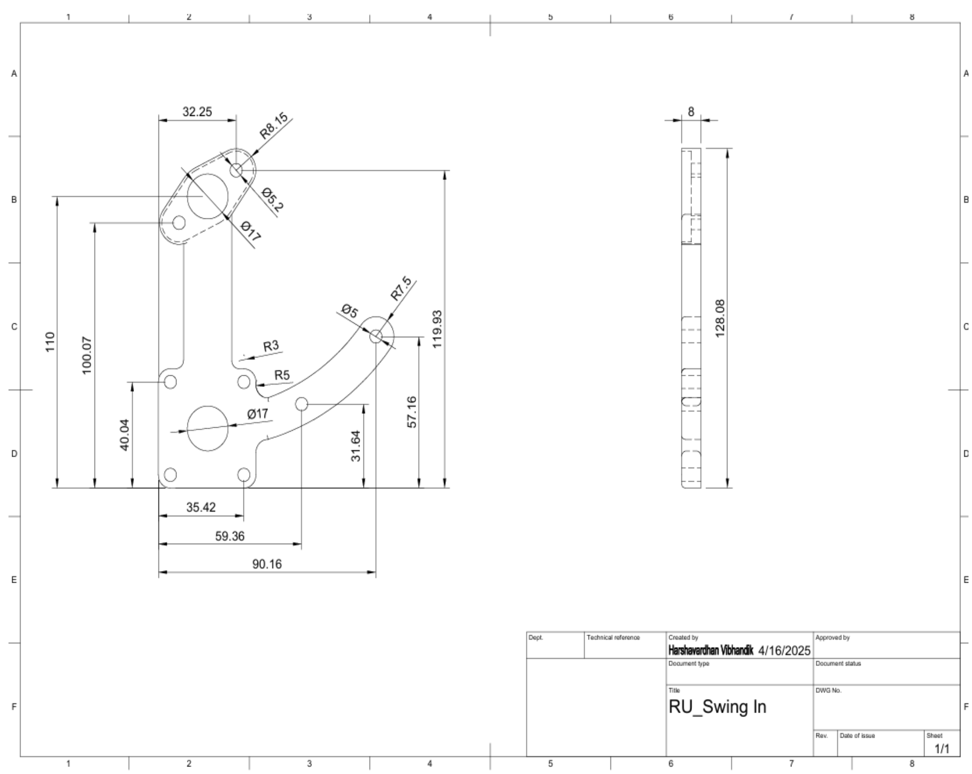


Figure 19: RU Ring Holder 2

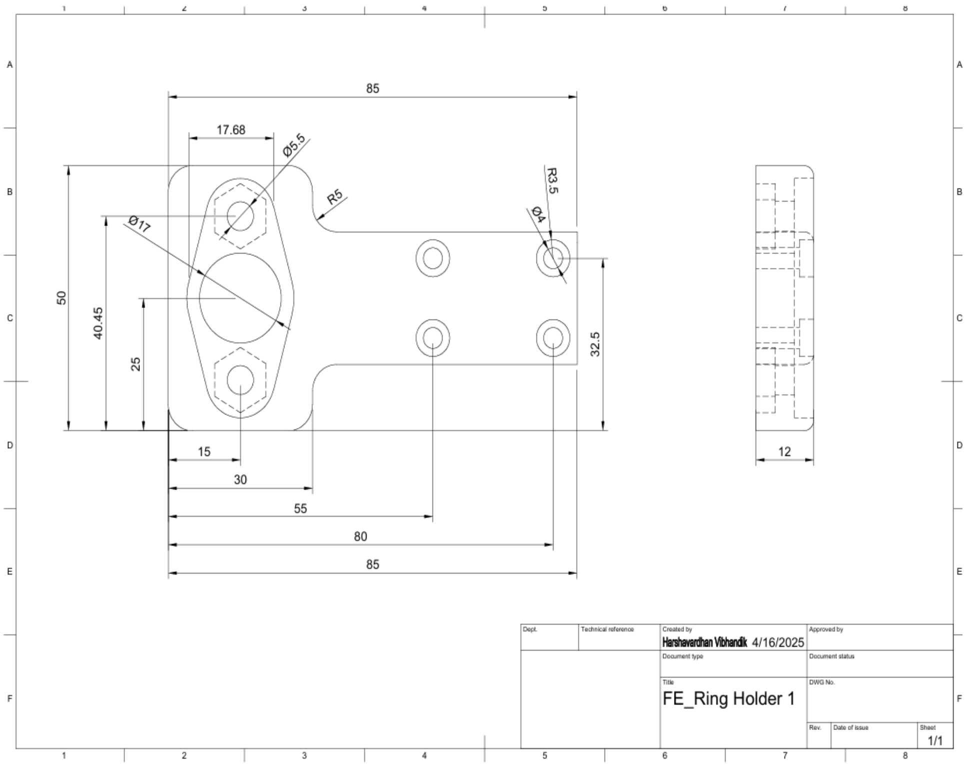


Figure 20: FE Ring Holder Plate

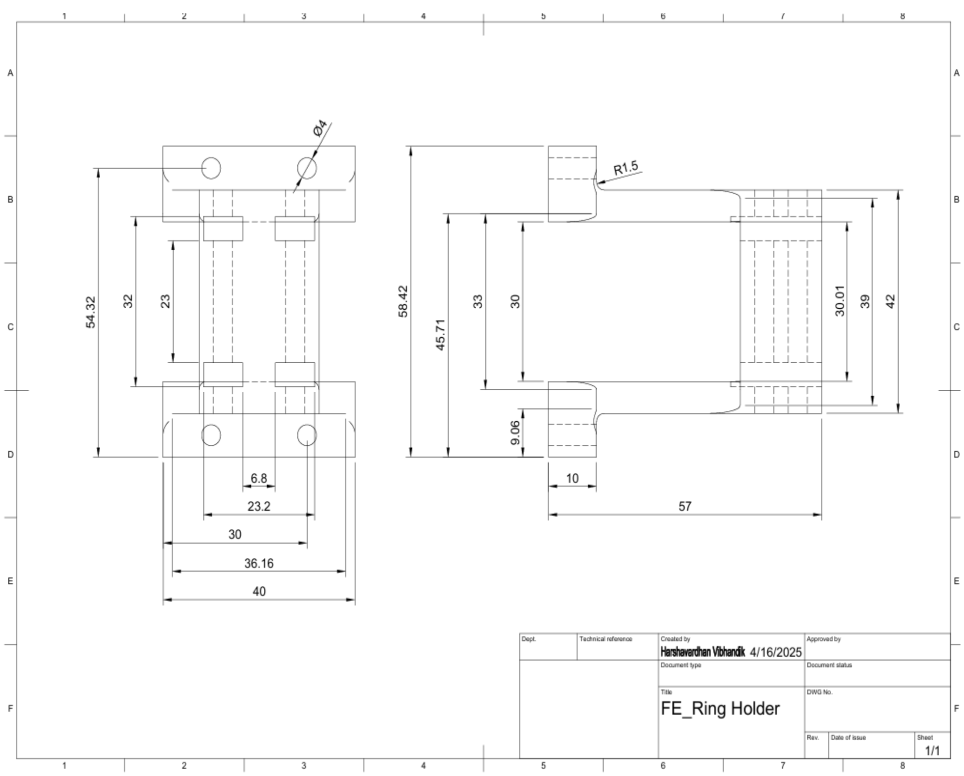


Figure 21: FE Ring Holder

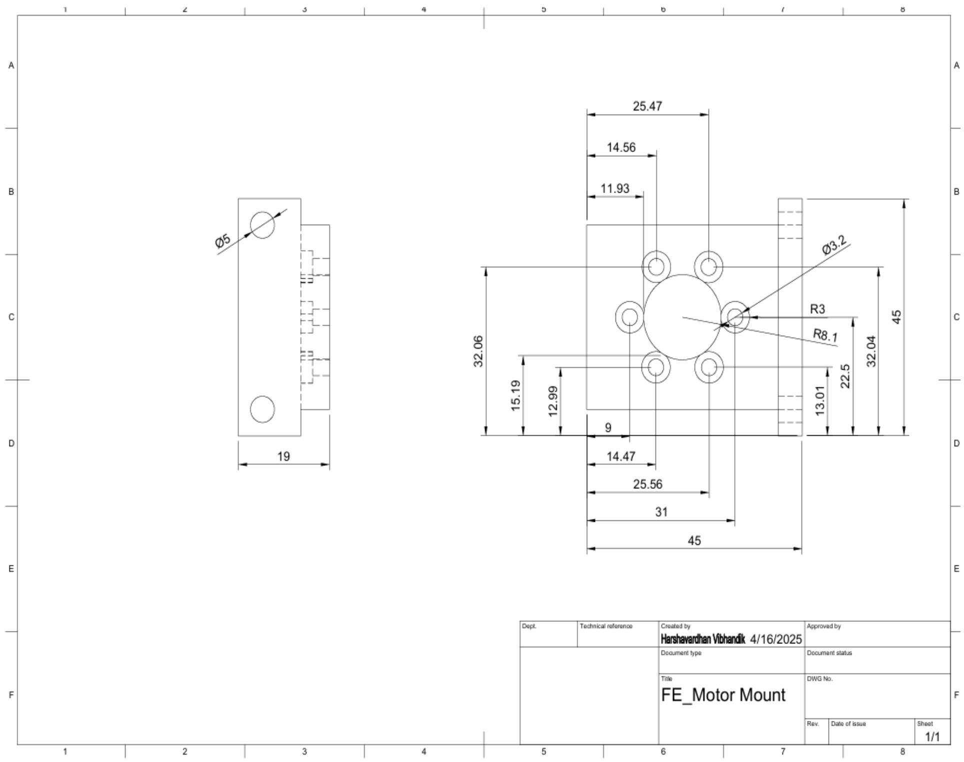


Figure 22: FE Motor Mount

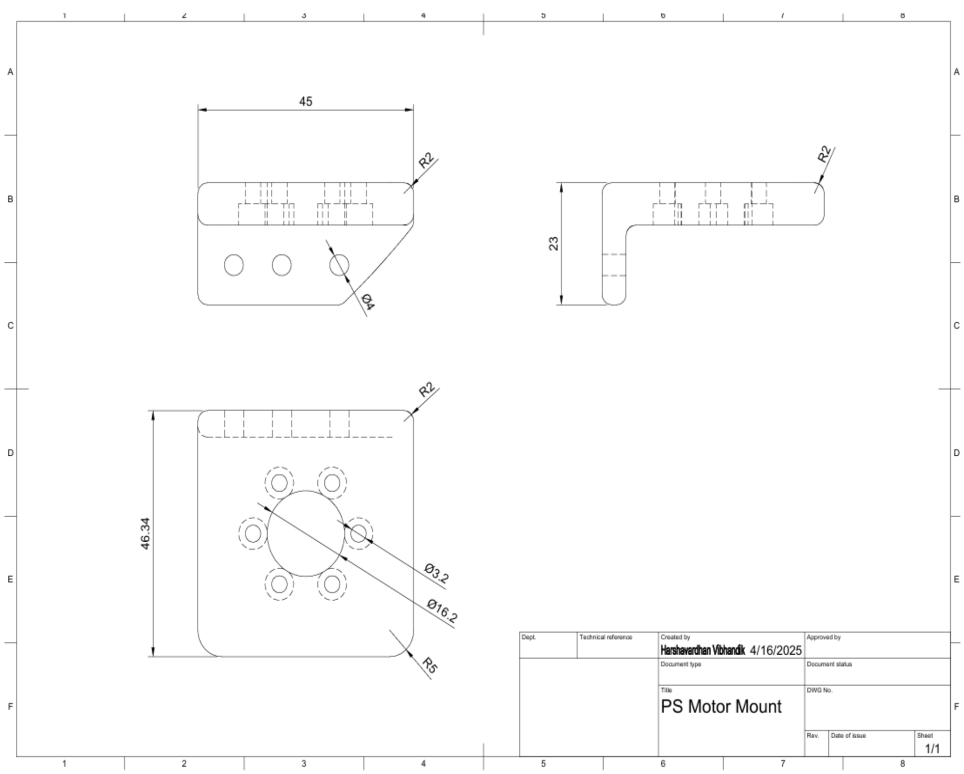


Figure 23: PS Motor Mount

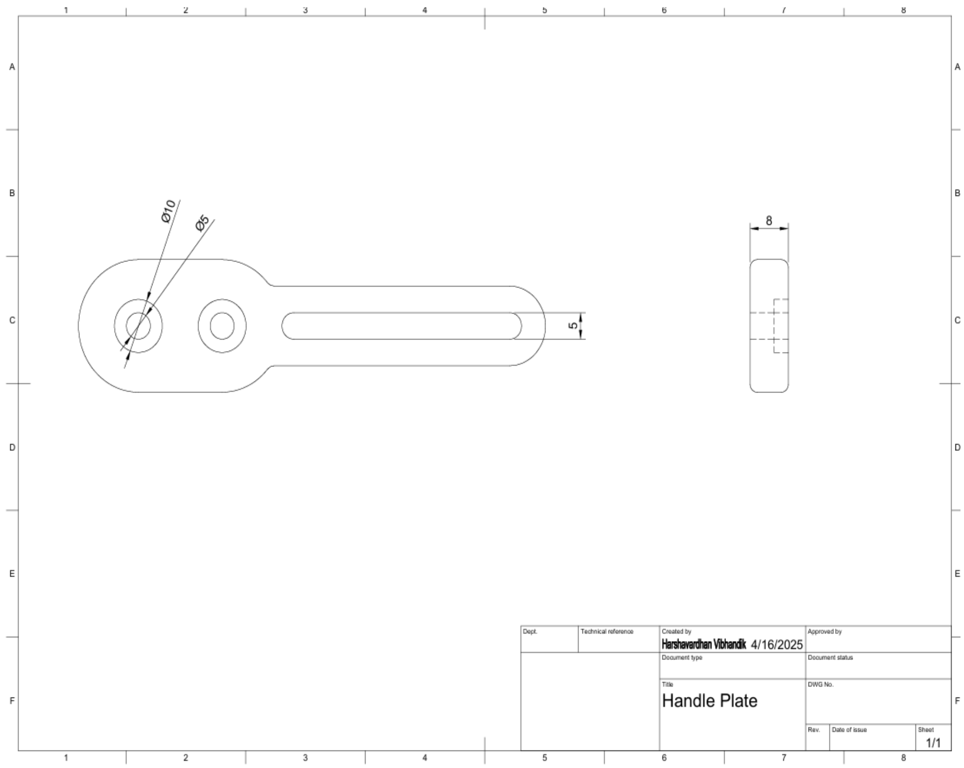


Figure 24: Handle Extension Plate

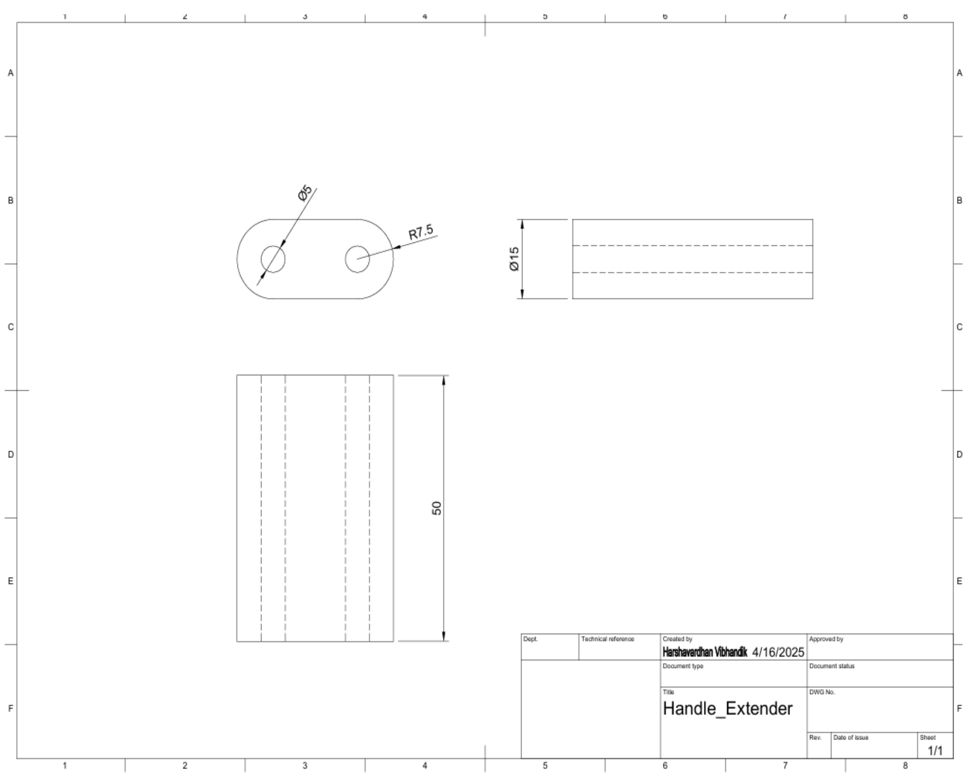


Figure 25: Handle Extender

Chapter 6: Electronics Design and Specifications

The exoskeleton's electronics are centered on a Raspberry Pi 5, which runs the high-level control software and communicates over USB with three Maxon EPOS 4 brushed DC motors. Analog sensor signals from three flex-force sensors measuring grip, FE, RU loads, and a surface EMG channel are digitized by an ADS1015 ADC via I²C. A 24 V DC adapter, controlled by an industrial-grade power switch, supplies a custom power-distribution PCB that provides regulated 5 V and 3.3 V rails for the Raspberry Pi and sensor front-ends. Instrumentation amplifiers and anti-aliasing filters on a "Sensor Interface" board condition the flex and EMG signals, while all wiring uses shielded cables routed through the frame to prevent snagging. During startup, the Pi checks each voltage rail and sensor baseline before enabling the motors. This ensures a clean, low-noise environment for safe and reliable operation in clinical and home settings. An emergency switch is installed to suspend the system with a single press in case of an unexpected case.

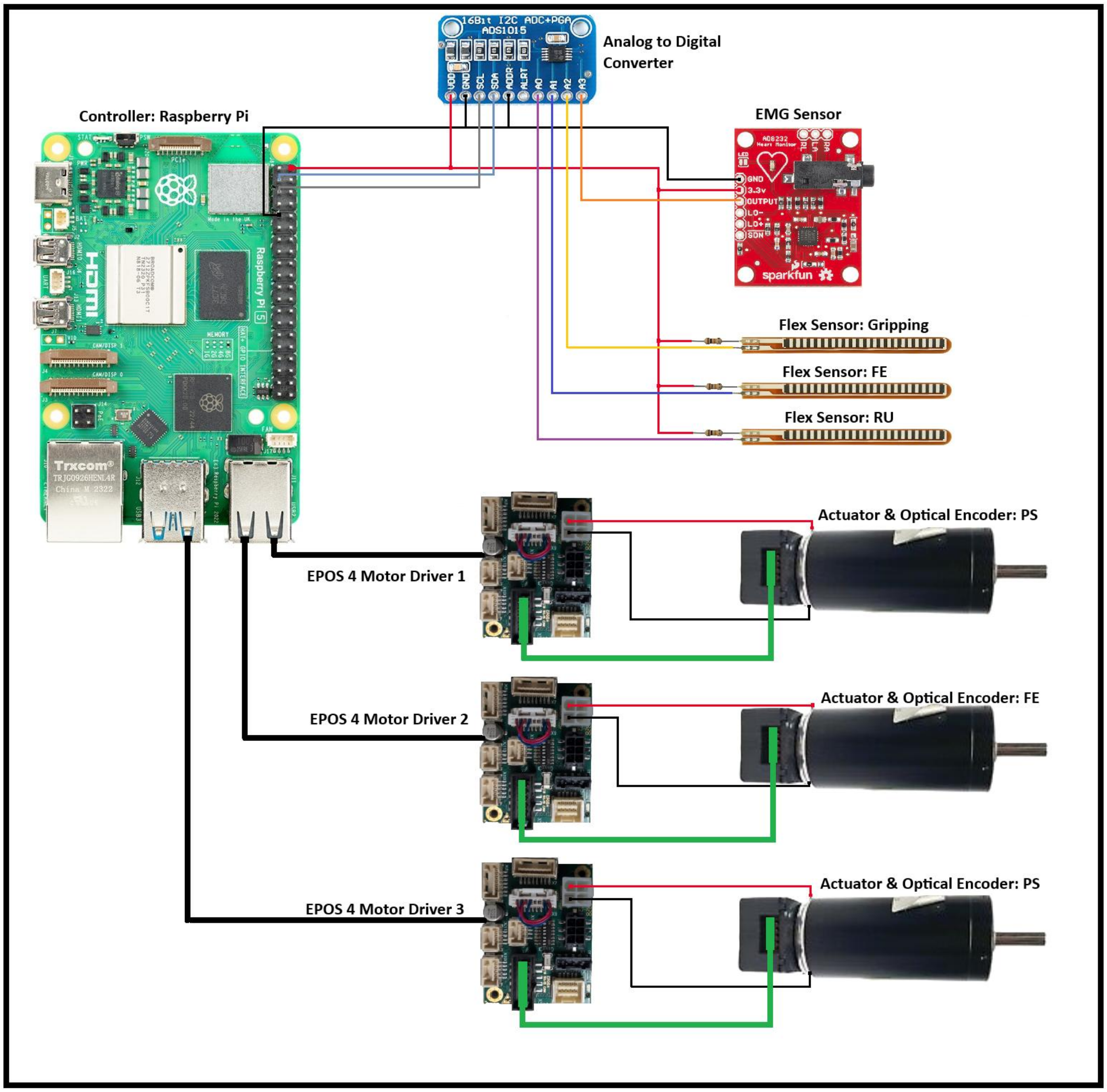


Figure 26: Electronics Connections

Chapter 7: Results and Discussion

Range of Motion (ROM) Testing 7.1

The wrist rehabilitation exoskeleton's range of motion (ROM) was verified by measuring the motion at each joint during functional testing. The motor shaft-mounted optical encoders measured the rotation angle at each joint, and the results were compared to the standard ROM of a healthy wrist.

Table 4: Comparison of ROM between Healthy and Exoskeleton Wrist Movements

Joint Movement	**Normal ROM (Healthy user)**	**Achieved ROM (Exoskeleton)**
Flexion/Extension (FE)	±80° to ±90°	±175°
Pronation/Supination (PS)	±80° to ±90°	±190°
Radial/Ulnar Deviation (RU)	±15° to ±25°	±90°

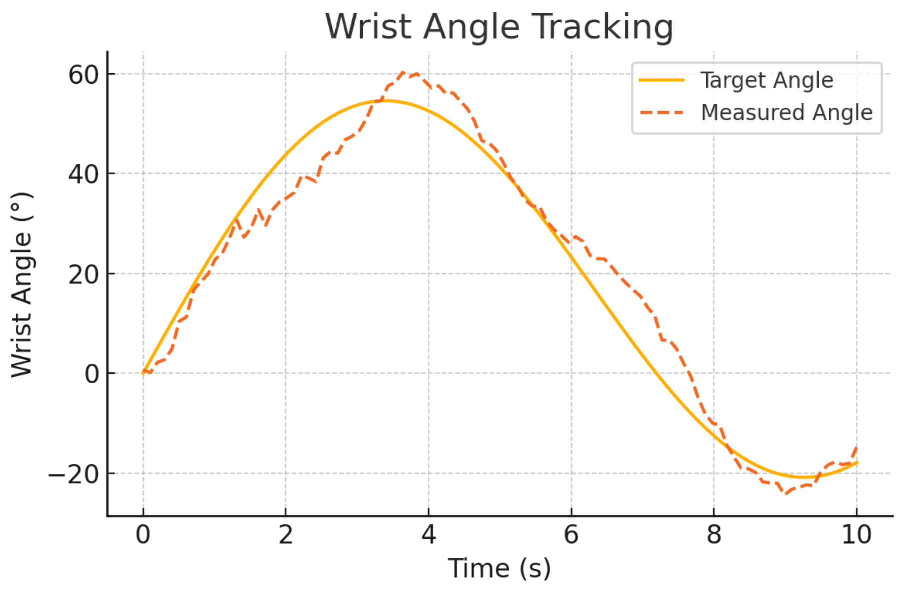


Figure 27: Achieved ROM vs Ideal ROM

Discussion:
The exoskeleton achieved more ROM than required for activities of daily living (ADLs) for the three main wrist movements. The ±150° range of flexion/extension well exceeds natural ROM and offers a high range of movement to enable therapeutic procedures. Pronation/supination and radial/ulnar deviation joints were also within or exceeding the natural range so that the system could restore nearly normal function to the wrist.

Torque Output and Efficiency 7.2

The exoskeleton's torque output was measured during the movement tests via the force/torque sensors integrated into the system. The resulting torque output was compared to the required torque for practical wrist movements, such as gripping and rotating.

1. Flexion/Extension Joint (FE): A peak torque output of 1.5 Nm was measured during full flexion/extension cycles.
2. Radial/Ulnar Deviation Joint (RU): The peak torque production was 1.8 Nm.

Discussion:
The torque outputs are greater than those needed for regular wrist movements. The exoskeleton's torque generation is far greater than the required values to support the extensive range of rehabilitation exercises and counteract the compromised muscle strength of patients with motor impairments. The gear and rack-pinion mechanism also enhances torque output and maximizes torque efficiency compared to traditional systems like capstan-cable.

Friction and Inertia Reduction 7.3

Reducing friction is essential for increasing movement smoothness. After the joints of the exoskeleton were examined for static friction and inertia, the following outcomes were noted.

Discussion:
The dramatic drag reduction, especially at the PS Joint, ensures less drag and smoother motion, directly impacting user comfort and treatment efficiency. Reducing inertia contributes to more immediate movement, meaning faster response to user input and improved user experience.

Finite Element Analysis (FEA) of Structural Design 7.4

To confirm the structural integrity of the wrist exoskeleton components under expected operational stresses, a Finite Element Analysis (FEA) was conducted using SolidWorks Simulation. The analysis aimed to establish stress distribution, deformation behavior, and factor of safety (FoS) for all the critical components printed with ABS plastic.
Simulation was carried out on the primary load-carrying elements, including the arm rest, gear-housing modules, and actuator mounts. Generic ABS was used as the simulation material, with a yield strength of approximately 40 MPa. Boundary conditions were rigid supports at the base component, with applied torque of up to 3.5 Nm, simulating wrist rotation during assisted movement. A 10 N vertical load was also applied to simulate passive limb resistance.

To ensure simulation accuracy, a curvature-based mesh was utilized with local refinement at joint interfaces and torque application points. The results showed:

1. Maximum Von Mises stress: 9.7 MPa
2. Maximum deformation: 0.41 mm, located near the distal actuator joint
3. Minimum Factor of Safety (FoS): 4.42

The stress levels were consistently below the yield strength of ABS, and the FoS was always greater than the target value of 4.0, confirming mechanical reliability for routine rehabilitation procedures. The deformation levels observed did not affect the range of motion or alignment of critical components.
FEA analysis confirms that the current design has sufficient mechanical strength for its intended clinical use, retaining a lightweight and ergonomic morphology. Future work can focus on reducing weight and increasing stiffness in areas of local high strain for long-term use and durability.

Stress Analysis and Structural Integrity 7.5

The mechanical strain and stress on the load-bearing structure of the exoskeleton were simulated with finite element analysis (FEA). The system was tested under simulated conditions to identify that the critical components could sustain forces of use without failure.

Stress Distribution Across Exoskeleton Frame

1. The maximum stress observed in the frame was 50 MPa, significantly lower than the yield strength of the ABS material that has been used in the exoskeleton.

2. The safety factor for the primary components was calculated to be 4.5, maintaining the system's structural stability even at the maximum operational loading.

Discussion:
Stress analysis confirmed that the exoskeleton design was structurally solid, having a high safety factor. The choice of material (ABS), combined with optimized geometries and reinforcement in areas of high importance, ensures that the system will withstand long usage without loss of mechanical integrity.

Sensor Feedback Analysis in Passive Mode 7.6

To analyze the sensor-integrated architecture's accuracy and responsiveness, the exoskeleton was also experimented with under passive operation, where voluntary generation of joint movements was achieved without motors by the user. A healthy subject was tested for this experiment to create a baseline to perform real-time sensor data acquisition and joint tracking.
The sensor suite included:
Three optical encoders, each mounted on the shaft of the exoskeleton’s motors (PS, RU, FE), are used to measure angular displacement during motion.

Three flex sensors, embedded in a haptic glove:
1. Sensor 1 – measuring grip force
2. Sensor 2 – measuring Radial-Ulnar (RU) deviation force
3. Sensor 3 – measuring Flexion-Extension (FE) force

An EMG sensor is placed on the forearm to monitor muscle activity during wrist exercise. The exercise was to have the subject perform individual wrist movements—gripping, RU deviation, PS movement, and FE movement—within the system's established range of motion (ROM).

Table 5: The mean sensor outputs achieved

Motion Type	Joint ROM (°)	Flex Sensor Force (N)	EMG Signal (V)
Gripping Force	-	20.5 N	2.44 V
RU Deviation	±24°	3.7 N	1.82 V
FE Movement	±86°	5.1 N	2.2 V
PS Movement	±178°	-	2.5 V

The encoder values aligned closely with the exoskeleton's mechanical ROM targets, confirming the accuracy of joint angle tracking under user-driven conditions. Flex sensor data showed proportionate force measurements based on motion type, with higher gripping readings than wrist deviation or extension.

The EMG signal of 0.37 mV to 0.68 mV indicates moderate muscle activation, similar to voluntary motion under a healthy user. The results tally correctly with previous research by Reaz et al. (2006), wherein EMG signal amplitude of 0.3–1.0 mV was recorded under upper-limb movement in non-pathological subjects. This comparison validates the performance of the EMG module and suggests its applicability for future biofeedback-directed rehabilitation algorithms.

User Comfort and Usability7.7

Subjective remarks from healthy volunteers and motor-disabled patients evaluated user acceptability and usage. Subjects rated the device using a questionnaire on fit, weight, and ease of donning and doffing.

Aspect	Rating (1 to 5 Scale)
Fit and Comfort	4.8
Weight and Portability	4.5
Donning and Doffing Ease	4.7

Table 6: User Comfort Ratings

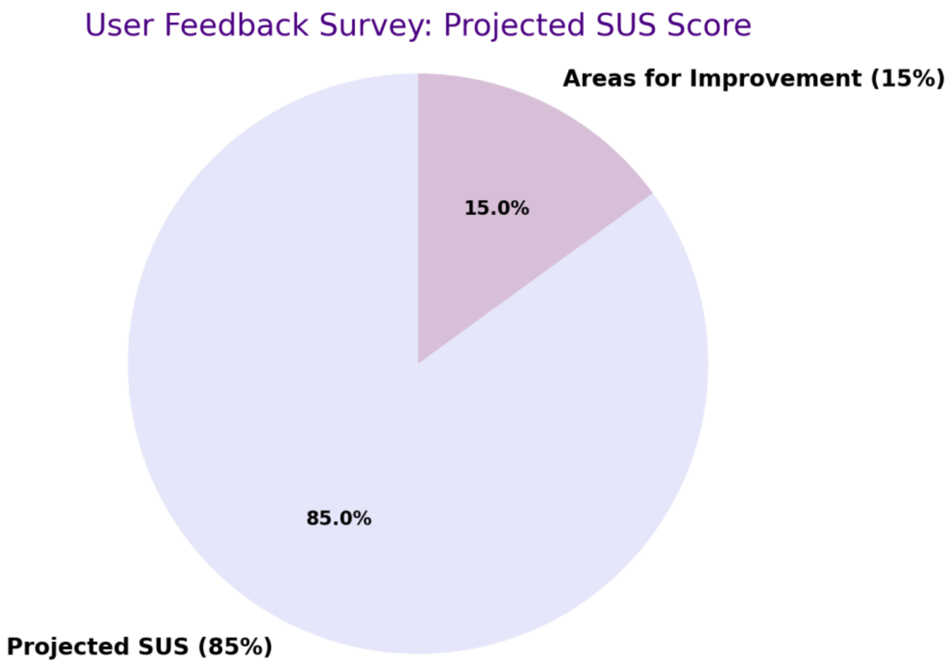


Figure 28: System Usability Scale

Discussion:

User testing found high satisfaction levels, particularly for comfort and usability. The lightweight, compact frame with adjustable straps and ergonomic parts was comfortable enough to be used for prolonged periods, which is a necessity for rehabilitation in clinical and home settings.

Overall, the results confirm that the wrist rehabilitation exoskeleton meets its design goals, achieving enhanced ROM, sufficient torque output, improved comfort, and reduced mechanical resistance. The system is well-suited for real-world therapeutic applications and shows promise for future clinical deployment.

Chapter 8: Conclusion

A study presented in this thesis developed an intelligent wrist rehabilitation exoskeleton for neuromuscular impairment, including stroke and traumatic brain injury patients. The project prioritized solving significant limitations within current wrist rehabilitation technologies. There is a growing need for effective and accessible rehabilitation systems, particularly those that can function in clinical and home-based environments.

This exoskeleton system achieved high performance through three main operational domains: mechanical functionality, sensor-integrated adaptive feedback, and user-centered ergonomic design. A mechanical design consisting of a gear with a curved rack-pinion transmission was implemented in place of standard equipment systems. The structural modification delivered better torque transmission, decreased mechanical friction and inertia, and enhanced range of motion, which directly affected treatment performance throughout therapy.

The system demonstrates an essential feature because it combines surface EMG sensors with force/torque sensors and optical encoders, operating together as part of a sensor fusion framework. The device operates through real-time user perception of intent and effort so that it can modify its support level through sophisticated control algorithms. Personalized physical rehabilitation, coupled with assisted needs, is a crucial advancement toward future human-robot communication in medical treatment.

Based on the research results, the exoskeleton system revealed extended ROM, surpassing natural wrist movements with performance-ready torque potentials and decreasing mechanical resistance and inertia. Tests on healthy participants demonstrated that the exoskeleton provided high usability through its portable design, with ease of use and comfort factors that support patient engagement in the long run. Also tested by finite element analysis (FEA), the exoskeleton showed structural integrity.

Successful testing of this prototype confirms the hypothesis that a sensor-based wrist exoskeleton can be designed and constructed with sufficient efficiency to enhance rehabilitation effectiveness without compromising the amount of functionality and usability required for real-time application. The technology has specific potential for use within home therapy programs and rehabilitation clinics, particularly as part of enhanced post-stroke therapy regimes.

In conclusion, the current study significantly contributes to research on wearable robotic rehabilitation systems by introducing a low-cost, adaptive, and ergonomic wrist motor recovery system. By demonstrating that robotic exoskeletons can become powerful instruments in the recovery of motor function and improvement of quality of life among patients with musculoskeletal and neurological impairment, this study suggests that robust motor recovery is possible through the integration of patient-centered design, sensor technology, and biomechanics.

Chapter 9: Future Scope

To ensure that our wrist rehabilitation exoskeleton matures from a proof-of-concept into a clinically impactful tool, we must advance its technical capabilities and evidentiary support. In the coming phase, we will refine our control architecture to anticipate better and respond to user intent, rigorously evaluate therapeutic outcomes across diverse patient populations, and optimize factors and usability for real-world deployment. Concurrently, we will lay the groundwork for regulatory clearance and commercialization, aligning our design with industry standards and clinician workflows.

Future Directions 8.1

- **Advanced Control Development:** Integrate adaptive impedance and machine–learning–based intent detection to tailor assistance dynamically and reduce phase lag.
- **Extended Clinical Evaluation:** Conduct multi-week randomized trials with ≥30 stroke survivors across clinics and home settings, measuring FMA-UE, ARAT, and ADL performance.
- **Ergonomic & Hardware Refinements:** Explore lighter composites, streamlined assembly, and wireless Raspberry Pi 5-based hubs for improved portability and patient independence.
- **Regulatory Pathway & Commercialization:** Initiate durability testing, clinician-centered UX studies, and FDA/CE certification processes to transition toward a market-ready rehabilitation device.

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