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Design and Analysis of a Bio-Inspired Assistive Exoskeleton for Enhancing Elbow Joint Mobility in Post-Stroke Patients

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ABSTRACT
The development of bio-assistive exoskeletons has become a crucial innovation in rehabilitation and mobility enhancement for individuals with upper limb impairments. This study presents the design, analysis and optimization of a bio- inspired elbow exoskeleton aimed at providing controlled support for arm flexion and extension. The exoskeleton incorporates a lightweight plain carbon steel frame, a rotary actuator and PID control system to ensure smooth, adaptive motion. Finite element analysis was conducted using SolidWorks to evaluate the structural integrity, load distribution and deformation characteristics under operational conditions. The maximum Von Mises stress was significantly lower than the material's yield strength, confirming structural reliability. The highest reaction force was observed in the Y direction of the exoskeleton, aligning with natural arm movement, while negligible deformation ensured durability and comfort. A servo motor with torque rating of around 10 nm was selected for actuation and a 12V, 4Ah lithium-ion battery provided the estimated operational time of 3.15 hours. The study demonstrates that a well-designed bio- assistive exoskeleton can enhance rehabilitation by providing reliable mechanical assistance while maintaining user comfort and efficiency.

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I. Introduction

1.1. *Study Background*

Stroke remains a leading cause of disability worldwide, with approximately 12.2 million new cases reported annually and nearly 62% of survivors experiencing persistent upper limb impairments (Feigin et al., 2021). Among these impairments, limited elbow joint mobility significantly affects functional independence, making tasks such as reaching, lifting, and grasping objects challenging (Caldwell et al., 2007). Traditional rehabilitation methods, including constraint-induced movement therapy and repetitive task-specific exercises, have demonstrated effectiveness in motor recovery but require intensive therapist supervision and prolonged training, often leading to patient fatigue and low adherence (Duret et al., 2019). Assistive exoskeletons, however, are close to a promising alternative by providing precise and repetitive movement assistance that improves motor relearning (Hussain et al. 2020). For instance, bio inspired exoskeletons, imitating human natural biomechanics, are found out to enhance neuroplasticity and joint function. These devices are based on biologically inspired principles of soft actuation and biomimetic control with smoother and more controllable motion and motion that mimics human movements. Given the high prevalence of post stroke disabilities and the limited effectiveness of conventional therapy, the rationale of using bio inspired exoskeletons in conjunction with rehabilitation strategies is based on potential benefits of increasing elbow joint mobility and improving the patient's quality of life.

With bio inspired robotics, some large improvements have been made regarding the design and effectiveness of assistive exoskeletons, specifically for upper limb rehabilitation. Firing of a robotic exoskeleton has been shown to enhance muscle activation patterns by up to 40% thus reducing muscle fatigue and exercising neuroplasticity (Chen et al., 2020). These are different from the traditional rigid exoskeletons since they include soft robotics and compliant actuators, which forms bio inspired models and allows for a more natural range of motion (Kim et al., 2019). Gopura et al. (2015) emphasize on how the integration of electromyography (EMG)—driven control mechanisms have improved the rehabilitation results by offering personalized help according to real time muscular activity. This is an adaptive capability, whereby movement support provided for stroke patients neither exceeds nor falls short, thereby preventing compensatory movements that could threaten the development of secondary complications such as spasticity and shoulder pain. In addition, the bioinspiration provides a pathway for deployment of emerging patient centered rehabilitation principles in which the assistive device serves as an enabler with support, rather than only mechanical support. However, there are still challenges to overcome with the exoskeletons such as remaining lightweight, cost effective, and accommodating a diverse patient population. To achieve the full clinical impact of a bio-inspired assistive exoskeleton, it is necessary to resolve these design and usability concerns.

Nevertheless, while there is a very promising potential for such bio-inspired exoskeletons to improve elbow joint mobility, there still exist several barriers to clinical adoption. According to the World Health Organization (2022) report, only 15% of the stroke survivors in the world have access to robotic rehabilitation technologies because of high cost and lack of infrastructure. Zhou et al. (2017), asserted that it is still a tough engineering task to design an optimal tradeoff between the torque output, lightweight construction, and ergonomic design. Device comfort, ease of donning and doffing and seamless integration with conventional rehabilitation protocols are also tied to long term user compliance (Vélez Guerrero et al., 2021). This research proposed the design and modelling of a bio assistive upper limb exoskeleton to address the challenges identified above, with the priorities of lightweight comfortable joint support. The design was developed and simulated in SOLIDWORKS and mechanically analyzed to ensure that the forces are optimally distributed and adaptive actuation is simulated. The goal of this research was to bridge that gap between technological innovation and practical implementation of affordable, practical, and accessible stroke survivor rehabilitative exoskeletons that provide independence and improve quality of life.

1.2 Problem Statement

Elbow joint mobility is persistently limited in poststroke patients, which seriously hampers their ability to perform daily activities and their quality of life. Current therapies involving rehabilitation of upper-limb movements are labor-intensive and available upper-limb exoskeletons fail to meet expectations regarding biomechanical adjustment, wearing comfort, and rigid design limits the ability for natural motion and usage (Kwakkel et al., 2019). However, these devices are cumbersome, costly, and not designed for long term use for many patients causing manifold restriction in their use (Hussain et al., 2020). In order to address these challenges, thus this study aimed to design a bio- inspired, assistive exoskeleton that is optimized for cost, comfort and multi-user adaptability. Aesthetically, the design incorporated a sleek structure, an appropriate load distribution and mechanical control to guarantee safety while making it easy to use. The exoskeleton is developed using SOLIDWORKS, and undergoes structural, biomechanical, and dynamic analysis to optimize the design of joint articulation and support mechanisms. This work aimed to develop an ergonomically efficient device, constructed with lightweight materials and adaptive systems, that enhances elbow mobility and rehabilitation outcomes through improving ergonomics, and by providing a solution that scales to support poststroke patients globally.

1.3 Objectives

Accordingly, the main goal of this project was to develop and optimize a bio-assistive exoskeleton that would facilitate upper limb movements with an emphasis on comfort. Specific goals included:

- ❖ Pioneering the design of an exoskeleton that has stable architectures for stability but flexible enough to allow free elbow joint motion.
- ❖ Assessing the mechanical stability and load-bearing capacity of the exoskeleton via Computer-Aided Design (CAD) modeling to inspect load comparison and actuation potency.
- ❖ Revising the design of the device in a way that will lower its price and make it more suitable to be used in rehabilitation or as an assistive technology.
- ❖ Enhancing user flexibility by adding mechanisms, which can be altered and adjusted according to the impaired mobility level.

This work aims at expanding rehabilitative and assistive robotics’ field by creating a comfortable, functional and portable exoskeleton for upper-limb disability patients.

Motor disabilities such as those from stroke or any other condition that impacts the upper limbs limit the functional capability of the affected person. Rehabilitation helps to restore functional ability but traditional intervention methods are time-intensive, costly, and not patient-centered (Díaz et al., 2021). While assistive exoskeletons constitute an interesting solution for functional augmentation of muscle force and assistance of coordinated joint support, these systems have been explored by integrating biomechanical and robotic principles. Most developments and trends in the current SWD have been oriented towards bio inspired designs, tendon driven actuation and adaptive control.

1.4 Bio-Inspired Design and Human Joint Kinematics

Bioinspired exoskeletons design seeks to replicate human biomechanics during natural motion, and help its users to regain natural and comfortable rehabilitation. Consequently, having these devices resemble the anatomy of the human body in its kinematics and muscle synergies has shown to improved rehabilitation outcomes (Zakaryan et al., 2021). For example, Zakaryan, et al. (2021) created a theoretical mechanical design for an upper limb exoskeleton aimed at natural elbow joint movement. They had introduced dual coupling to their work, which helps to enforce synchronization between the exoskeleton and the residual limb so as to avoid interference and achieve smooth motion. In addition to improving biomechanical compatibility of the device, this approach also reinforced the effectiveness of the device in post stroke rehabilitation. A model of an upper limb exoskeleton system is represented in figure 1 incorporating Hill's type artificial muscles, demonstrating the integration of bio-inspired principles into exoskeleton design (Zakaryan et al., 2021).

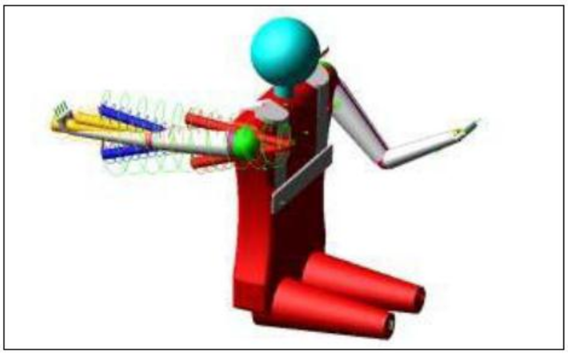

Figure 1:A model of the upper-limb exoskeleton system with Hill's type artificial muscles (Zakaryan et al. 2021)

The tendon driven actuation system based on the bio-inspired exoskeleton has conventionally been used to represent the elasticity and extensibility of the biological tendons. Veale and Xie (2016) worked through various categories of actuation approaches and concluded that tendon driver actuation is less invasive with enough slack to fit in upper extremity exoskeletons. Unlike natural movement constrained by common rigid structures that enforce lack of comfort, tendon-based approaches present low mechanical resistance and allow large freedom of motion giving way to smoother and more comfortable motion. Especially for that application in stroke rehabilitation, where the patients often suffer from muscle stiffness and spasticity (Veale & Xie, 2016). Moreover, Copaci et al (2017) demonstrated the use of inverse kinematic models to establish control for exoskeleton movements that imitate the human motor patterns very closely. This capability makes the rehabilitation exercises more physiology specific to the patient, and so improves the recovery outcome and also lessens the chances of secondary injury.

These features of exoskeleton technology constitute major steps towards bio inspired design principles and tendon driven systems as a means of actuation. To overcome these shortcomings of typical rigid designs that do not adjust to the changes in muscular tone and joint stiffness in post stroke patients, these advances are made. Developing more efficient, as well as individualized rehabilitation strategies is done by using bio inspired exoskeletons that utilize natural movement patterns and biomechanical compatibility. Using Hill's type artificial muscle and inverse kinematics, it is possible to adapt the device to be unique for each patient (Copaci et al., 2017). Not only does this level of adaptability help the device, but it also helps the patient compliance and engagement which are well known critical factors for successful rehabilitation. Therefore, bio inspired exoskeletons are promising to revolutionize post stroke recovery as a comfortable, efficient and patient centric upper limb rehabilitation.

1.5 Actuation and Control Strategies

Exoskeletons are subjected to careful effort in their optimization as supportive structures and attachment methods are being explored as well as force distributions and energy efficiency to enable efficient rehabilitation. This represents a key advancement in the area, as torque-controlled exoskeletons enable the very precise regulation of the support provided to the patient. Vitiello et al. (2013) prototyped a torque- controlled powered exoskeleton in order to illustrate the importance of variable torque control in motor rehabilitation. They demonstrated in their experimental results that by varying the level of support according to the patient's mobility, the exoskeleton can eliminate overburden on the user while promoting recovery. For patients who have suffered a stroke, this adaptability is especially important since these patients are characterized by varying degrees of muscle strength and joint stiffness. Figure 2 (Vitiello et al., 2013) shows an upper limb powered exoskeleton which includes integration within torque control mechanisms for personalized, and dynamic support throughout rehabilitation.

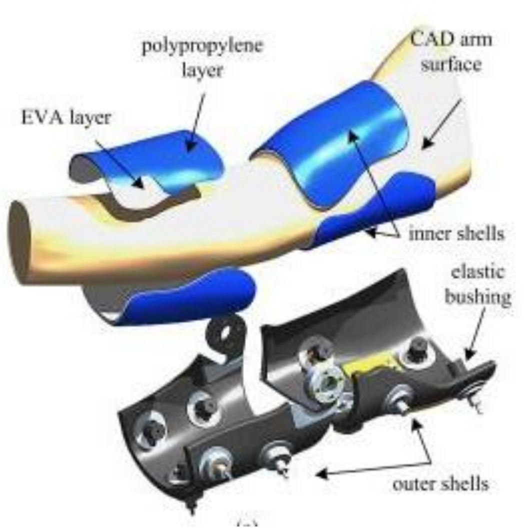

Figure 2: Most upper limb powered exoskeleton (Vitiello et al. 2013)

Additionally, assistive control strategies have been proposed to improve the effectiveness of the exoskeletons. Support is only offered when needed, so that patients are more involved in their own rehabilitation. An augmented intelligent assistance system that adapts based in real-time to the user's performance was developed by Delgado and Yihun (2023). They introduced the notion of complexity adaptation, which cuts down the amount of assistance eventually as the patient gets better on its feet. By increasing the amount and quality of patient engagement and optimizing rehabilitation outcomes through suitable exoskeleton assistance level at suitable times, this approach improves rehabilitation outcomes. The development of such smart regulating systems represents an important step beyond solely effective and at the same time motivating patient centered rehabilitation programs.

Another important aspect of modern exoskeleton control strategies is real- time sensor integration. Furthermore, Díaz, Gil, and Sánchez (2021) highlighted the need for embedding sensors that allow the exoskeleton to adjust itself dynamically in response to its user's movements. Overall, these sensors give continuous feedback allowing the device to adapt its support according to changes in the patient's condition. By personalizing this level of rehabilitation programs, it ensures that each patient is provided with a unique program that takes on their unique needs greatly boosting program effectiveness. By combining torque control, assist-as-needed strategies, and real-time sensor feedback, modern exoskeletons can deliver highly adaptive and efficient rehabilitation, addressing the unique challenges faced by post-stroke patients and improving their chances of recovery.

1.6 Structural Optimization and Performance Evaluation

Exoskeleton design is the careful balancing of the amount of structural support needed without driving wearer discomfort or obligating them to acclimate to it. This can only be achieved if the device is rigid enough to survive operational loads during extended use yet flexible and lightweight enough to conform to the user's motion. Assessment of the fatigue capacity and durability of mechanical components has become essential and Finite Element Analysis (FEA) offers an efficient tool for stress analysis. For instance, Copaci et. al (2017) used FEA simulation to inform material selection and decide on designs that were more durable and light weight for robotic exoskeletons. This enables a designer to spot potential points of stress and optimize the structure so as to avoid mechanical failure but remain comfortable for a user. The use of FEA enables exoskeletons to be designed to satisfy the dual objectives of robustness and ergonomic efficiency, including the ability to perform for long sessions.

Another crucial consideration in exoskeleton design is energy efficiency since it affects the usability and performance of the device. The power consumption is generally calculated as $P = T \times \omega$, involving power (P), torque (T), and angular velocity (ω). Tang et al. (2023) examined the use of neuromuscular control strategies for improving energy consumption in upper limb exoskeletons. Their research showed that bio inspired actuation systems can achieve such reductions in power coupling and allow efficient muscle activation as part of rehabilitation without a significant increase in energy use. In addition, this improves the device's performance and prolongs its operational life and makes the device more practical for clinical and home-based rehabilitation. Exoskeletons integrate energy efficient technologies to support the user for sustained periods of physical activity without restricting the user in comfort and freedom of mobility.

Besides structural and energy considerations, clinical effectiveness of exoskeletons has been extensively studied. Nine commercially available bioinspired wearable robotic devices for stroke rehabilitation were systematically reviewed by Bardi et al. (2022). Using wearable exoskeletons coupled to task specific rehabilitation exercise, they found that the benefits of the exoskeleton extend to muscle activation and motor function of the participants. Specifically, these devices were useful for improving upper-limb mobility and coordination and provided an important platform for stroke recovery. It also underscores the potential to maximize outcomes through pairing of exoskeleton technology with targeted rehabilitation protocols. Modern exoskeletons are evolving to be highly effective and user-friendly solutions for improving mobility and quality of life for post stroke patients by combining structural, energy, and clinical performance parameters.

1.7 Soft Robotics and Future Trends

Over the last few years, exoskeleton body layouts have shifted to softer, more flexible, comfortable, and biomechanically compatible layout rather than the bulky and rigid layouts seen in the past. To fabricate devices that are capable of seamlessly integrating with the human body, and perform effectively in rehabilitation, there needs to be shift in design and manufacturing trends. An example is provided by Tanczak et al. (2025) whose work compared the advantages soft robotic exoskeletons offer over conventional ones by having greater flexibility and biomechanical compliance. The actuated soft materials and soft actuators not only decrease discomfort but increase the user's control over the device, allowing it to be effective in such extended rehabilitation sessions. Special fitness tracking systems are more useful to post stroke patients, as stroke patients need long term therapy to get mobility back. Soft robotics are introduced into exoskeletons to enhance the ability to mimic the natural human motion, to make the rehabilitation process more intuitive and more comfortable.

The second major trend on the path to the next generation of exoskeletons is the inclusion of artificial intelligence (AI) or adaptive control systems in addition to soft robotics. For upper limb rehabilitation, Shinde et al. (2024) considered bio inspired robotic exoskeleton with electrical adaptive control. Their work highlighted the contribution of AI integrated sensor systems which provided real time muscular feedback that can continuously monitor progress of the patient. This enables the dynamic adjustment of rehabilitation program to maintain relevance to the patient's changing needs. Integrating soft robotics and smart control systems is a significant step forward toward creating a personalized and adaptive rehabilitation plan that is needed for optimizing outcome of recovery. These innovations also improve patient engagement and adherence to therapy as well as increasing effectiveness of exoskeletons.

The future of the exoskeleton technology is in the soft robotics as well as intelligent systems, which also has the potential for pioneering the effects of rehabilitation. These flexible, advanced actuator and AI driven control strategy-based exoskeletons allow more comfortable, user friendly, and highly effective exoskeletons that support motor recovery. Advancement in these directions is expected to improve some of the major disadvantages of the typical exoskeletons, namely discomfort, little adaptability, and high cost. Following the existing path of developing technology, soft robotic exoskeletons with intelligent control system are going to act as means for personalized and effective rehabilitation and as a viable alternative hope for stroke patients and patients with other mobility disorders.

1.8 Challenges and Future Directions

Despite significant progress in bio inspired exoskeletons, there are still barriers that prevent general use of the exoskeleton in mainstream rehabilitation programs. The key issues include flexibility, compactness, and affordability, vital to make inventory more accessible to a large population. However, due to their reliance on external power sources, contemporary designs are constrained by inability to be mobile and by higher operational complexity, in addition to being affected by higher production costs, limiting their widespread implementation (Tagliamonte et al., 2019). To overcome these deficits, future research should aim to fuse soft robotics, high energy density actuators and AI driven smart control systems in order to improve productivity as well as cost effectiveness. However, there is a demand for more thorough clinical trials analyzing the long- term prognosis of exoskeleton assisted rehabilitation, in regards to clinical reintegration and patient adherence to therapy programs. The results of these studies will be valuable for their real-world effectiveness and further development of exoskeleton devices.

Therefore, these challenges can be overcome through future research focusing on several key areas. To improve the energy autonomy of exoskeletons, smart actuators need to be developed that consume less power while achieving high efficiency. Secondly, technical refinements are required for these devices to become practical in terms of reliability, cost of production and affordability for a broader audience. Thirdly, clinical trials will be extended to gauge long term rehabilitation outcomes in order to assess the uses and limitations of technology. Adaptive control techniques using artificial intelligence, as well as soft robotics structure, and will be used in future exoskeletons. The innovations that these devices introduce will make future devices as comfortable and energy efficient, and will allow future devices to personalize individual patient needs by delivering customized rehabilitation.

Mobile assistive exoskeletons using the concept of biological design provide stroke rehabilitation in an adaptive, efficient, and user-friendly manner. Significant improvements such as tendon driven actuation systems, real time control, and soft robotic structures have been developed to boost performance, portability, and comfort of these devices. Nevertheless, their wide adoption is also constrained by power consumption, cost, and portability issues. More studies in the future should explore the use of AI to provide advanced control systems, optimize the demand for power during the rehabilitation and clinical trials in a large scale to validate their effectiveness in real world settings. Addressing these challenges can lead to the promising application of bio-inspired exoskeletons as a transformative tool in post stroke rehabilitation, and promise hope and improved quality of life to millions of patients worldwide.

II. METHODOLOGY

2.1 Bio-assistive Exoskeleton Configuration

2.1.1 *Exoskeleton Frame.* A kind of wearable technology where bio-assistive exoskeleton can offer mechanical support and assisted movements for the elbow joint of the post stroke patients. The design for this project employed an actuated elbow brace that holds the overall support, motion tracking sensors, the control unit and a wearable frame for the patients. It replicated the natural movement at the elbow joint to integrate the rehabilitation exercises in harmony with the patient. It stays involved in the flexion and extension of the elbow, however, in situations when the muscle power is reduced, the actuator comes into play. The structure in support of the exoskeleton design comprised reliable materials like plain carbon steel to ensure structural integrity. The design also featured 3 straps made of neoprene material. The straps would be used to fasten the exoskeleton to the arm. Each strap was adjustable to suit user needs while providing optimum comfort as illustrated in figure 3. The elbow joint was fitted with a servo and an actuator to power the exoskeleton for flexion and extension while in use.

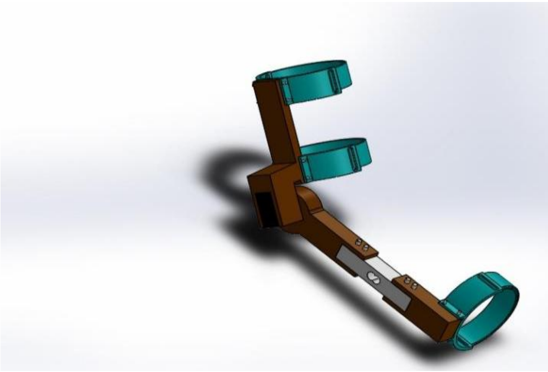

Figure 3: Bio-assistive exoskeleton configuration

2.2 Exoskeleton Component Design

2.2.1 *Exoskeleton Frame and Joint Mechanism***.** The basic component was the exoskeleton framework that included one motorized joint capable of providing normal movement support. The design considerations included:

2.2.1.1 Material selection: plain carbon steel is used because it is a high strength material and does not exert much pressure on the user.

2.2.1.2 Prosthetic design: Adjustable and modular forearm and upper arm sections to accommodate varying limb sizes.

2.2.1.3 Elbow Joint: A rotary haptic actuator that makes sure that a controlled force can be applied during the flexion and extension movement of the elbow joint.

Torque output at the elbow joint was computed based on biomechanical parameters defined for a human arm and corresponded to the angle of motion. Since rotation was involved at the elbow joint where the upper and lower arm segment meet, a bearing would be installed to ensure there is free space to facilitate rotation.

2.2.2 ***Actuator and Control System.*** The actuator system was designed to help the elbow by providing the required torque to enable it bend or rotate. The design considerations included using a servo motor for that purpose and a control system to modulate the force output during mobility. A wireless lower extremity rehabilitation device would be used to track the movement of the user and afford rehabilitation exercises depending on feedback picked from sensors.

2.2.3 *Power and Battery System.* The exoskeleton was powered by a lightweight lithium-ion battery designed for extended operation. The power management system ensured stable voltage regulation to maintain efficiency, low-power consumption to extend battery life and rechargeability for convenience and long-term use.

2.3 System Design Calculations

2.3.1 *Torque Calculation for Elbow Assistance.* The torque required at the elbow joint is estimated using the torque equation:

$$T = F\ x\ r$$

Where:

- T = Torque (Nm)

- F = Required force to move the arm (N)
- r = Moment arm (m), distance from elbow joint to forearm center of mass

For this design project, the Forearm weight is taken to be 15N and the moment arm is taken to be 0.25m. Hence

$$T = 15x0.25 = 3.75Nm$$

This torque determines the motor power rating required for efficient assistance.

2.3.2. Power Consumption of the Actuator. The mechanical power required to drive the elbow movement is calculated as:

$$P = T \; x \; \omega$$

Where:
- P = Power (W)
- T = Torque (Nm)
- ω = Angular velocity (rad/s)

Considering a reasonable estimate of human elbow joint motion during rehabilitation exercises based on range of motion and estimated time for one elbow flex, the angular velocity used will be 1.5 rad/s. Hence

$P = 3.75 \; x \; 1.5 = 5.625W$
Considering a motor efficiency of 0.85, the required power input is

$$P_{input} = \frac{5.625}{0.85} = 6.62 \; W$$

This value will help to determine the battery capacity and energy requirements for extended operation. Based on the above calculated values, a suitable actuator for this application would be he Dynamixel-P Series Servo Motor (P42-020- S300-R)**,** which has:

- Torque Rating: 10.2 Nm
- Speed: 1.5 rad/s (with proper gearing)
- Power Rating: 15W (sufficient for load variations)
- Voltage: 24V
- Control: Supports PID tuning for precise motion control

This actuator provides enough torque, operates efficiently within the power constraints, and allows easy integration into control systems.

2.3.4. Control System Optimization. The Proportional-Integral-Derivative (PID) controller was implemented to ensure smooth and adaptive motion. The controller gains are adjusted using Kp, Ki, Kd

Where:
- Kp = Proportional gain (controls response speed)
- Ki= Integral gain (reduces steady-state error)
- Kd=Derivative gain (minimizes overshoot)

A closed-loop system ensures precise assistance levels, adapting to user movement for enhanced rehabilitation effectiveness. Utilizing a practical approach such as the Ziegler- Nichols tuning method which involves increasing proportional gains of the system until it oscillates at a constant amplitude. Th PID controller would be used to adjust the motor behavior to improve response speed, minimize error and prevent overshoot. For a PID controller the Kp, Ki, and Kd were calculated as follows based on standard formulas.

$K_p = 0.6 \, K_u$

$K_i = 2K_p / T_u$, $K_d = K_p T_u / 8$

The calculated values for the exoskeleton include

Ultimate gain (K_u) = 10

Oscillation Period (T_u) = 0.5 sec

Hence the calculated gains become:

$$K_p = 0.6 \; x \; 10 = 6$$

$$K_i = 2x\frac{6}{0.5} = 24$$

$$K_d = 6 \; x \; \frac{0.5}{8} = 0.75$$

This tuning ensured that the exoskeleton provides precise assistance, smooth movement, and quick adaptation to user needs.

3.3.4. Battery Life Estimation. Battery capacity is calculated based on power consumption.

$$Battery\ Life = \frac{Battery\ capacity\ (Wh)}{Power\ consumption}$$

Taking a 12V, 2Ah lithium-ion battery,

$$Battery\ Life = 12\ x\ 2 = 24Wh$$

With 6.62W power consumption:

$$Battery\ Life = \frac{24}{6.62} = 3.63\ hours$$

This ensures the system operates for a sufficient period before recharging.

2.4 Finite Element Analysis
2.4.1. Simulation Set up. SolidWorks simulation was used to perform a static analysis of the exoskeleton using Finite Element Analysis technique. The solver used was the FFEPlus (Finite Element Analysis Plus) with a solid mesh setting. Force and torque were the primary external forces applied on the exoskeleton to model the loads it would bear when in use. A force of 15N was applied on the forearm to illustrate the weight of a human arm. Gravitational force of 9.81N was also applied in the forearm in addition to a moment of 3.745 N.m applied at the elbow joint. To run the static study, fixed geometries were applied on the straps and upper arm segment. A fixed hinge was applied at the elbow joint to allow movement during the simulation. The materials selected for the simulation included:

- Plain Carbon Steel for the exoskeleton lower and upper arm joints
- Neoprene for the arm straps
- Galvanized steel for the stud fasteners connecting the upper and lower arm sections

A global bonded contact was used to keep all the parts of the assembly intact during the simulation process. An element size of 5.23547mm was used during the meshing process, with total nodes and elements obtained being 64,874 and 34,262 respectively.

Figure 4: Solid Meshing of the Exoskeleton

II. Results And Discussion

3.1 Finite Element Analysis Results

Running the simulation produced key results that illustrate how the exoskeleton would perform under real operational conditions. The loads applied produced a reaction force in three directions within a cartesian plane. The reaction force in the X direction was -0.845366 N, indicating minimal forces in that direction. The reaction force in the Y direction was the 27.804 N, indicating that the applied loads exert the greatest force in the Y direction, which is the direction the arm flexes up and down. Reaction force in the Z direction was 0.08 N, indicating minimal effect of applied loads in this direction. The resultant force at the elbow joint was 4.28 N, due to the differences in direction of movement between the lower and upper arms of the exoskeleton. The external loads also produced a resultant force of 2.699 N on the upper arm, which had a fixed constraint applied during the simulation.

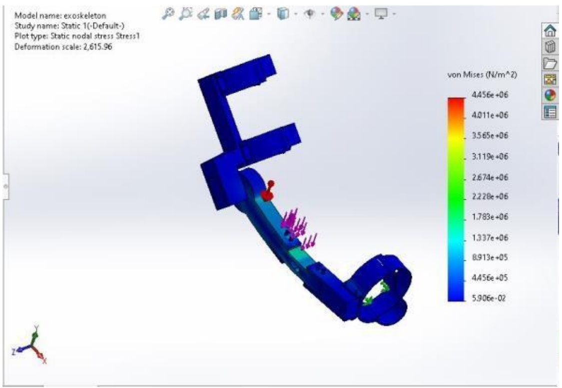

Figure 5: Von Mises Stress Results

The Von Mises Stress obtained from the simulation ranged between 5.906 x 10^{-2} N/m^2 to 4.456 x 10^6 N/m^2 on the upper limit as indicated in Figure 5. The stress values obtained were well within the yield strength of plain carbon steel which is 2.20594 x 10^{8} N/m^2. This indicated that the maximum stress

obtained in the exoskeleton,
4.456 MPa, is much lower than the yield strength 220.6 MPa for plain carbon steel.

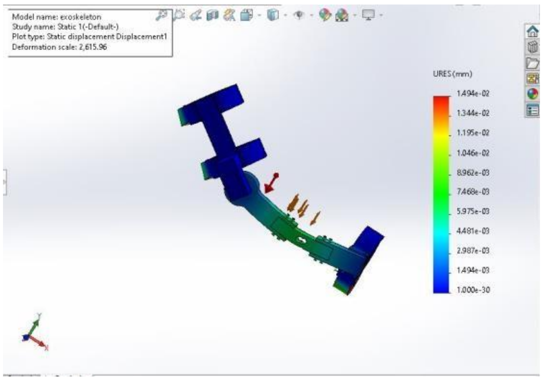

Figure 6: Deformation results

The deformation values obtained from the simulation ranged from a minimum of 1.00 x 10^{-30} mm to a maximum of 1.494 x 10^{-2} mm, indicating insignificant deformation for the exoskeleton when in use as illustrated in Figure
6. This indicated that the design would handle external loads with minimal deformation thereby ensuring reliability.

3.2 Conclusions

Structural Integrity: The exoskeleton remained well within the material limits, as the maximum Von Mises stress (4.456 MPa) was significantly lower than the yield strength (220.6 MPa) of plain carbon steel, ensuring safety and durability. This indicated that the material selected was appropriate and that no plastic deformation would occur under applied forces.

Load Distribution: The highest reaction force (27.804 N) occurred in the Y-direction, aligning with the primary motion of the arm, confirming that the design effectively supports flexion and extension. Minimal reaction forces in the X (- 0.845 N) and Z (0.08 N) directions indicated that the structure was well-balanced and did not experience excessive lateral or torsional forces. The resultant force at the elbow joint was 4.28 N, confirming that the design effectively manages force transitions between the lower and upper arm. The external loads produced a reaction force of 2.699 N on the upper arm**,** which was constrained, indicating proper load transfer and stability.

Minimal Deformation: The maximum deformation (0.01494mm) is negligible and thus shows high rigidity and stability for operational loads which ensures continuous and consistent performance without the failure of the structure. The exoskeleton was very stiff and it kept the same shape under operational conditions, assuring a uniform performance without excessive flexing or bending.

Reliable Performance: Long term use of the exoskeleton would reduce wear on any structural members, and its ability to successfully distribute loads through its structure, while maintaining geometric shape revealed that it was reliable, durable, and capable of seamless real-world applications without any material reinforcements.

IV. CONCLUSION

Bio inspired exoskeletons have the potential to improve rehabilitation outcome in individuals with upper limb impairments, especially in the area surrounding the upper limb. The aim of this thesis was to design, analyze and optimize a bio-assistive elbow exoskeleton with integration of key biomechanical principles, advanced control strategy and structural performance evaluation. The exoskeleton was designed with a plain carbon steel frame and a rotary actuator to provide controlled support during elbow flexion and extension. The material selection¸ particularly plain carbon steel for structural components like arm supports ensured high strength and durability while maintaining a lightweight and comfortable design. Fine element analysis confirmed the maximum stress to be
4.456 MPa which was well below the ultimate yield strength of the material. The highest reaction forces observed in the Y direction indicate that the primary movement of the arm is in this direction which would enable the exoskeleton to support flexion and extension. Minimal reaction forces were observed in the X and Z directions, indicating that the design was and well balanced with negligible lateral forces. A PID controller was used to ensure smooth and adaptive motion while allowing real-time adjustments based on user needs. A servo motor would be used to provide the power needed to operate the exoskeleton. A 12V, 4Ah lithium-ion battery provided an estimated operational time of 3.15 hours, making the system practical for extended rehabilitation sessions. This study demonstrated that a well-designed bio-assistive exoskeleton can provide effective support for elbow joint rehabilitation.

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