Development of an occupational upper-limb exoskeleton

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Declaration of own work

I declare that the work in this MSc dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

Adip Ranjan Das, 05/09/2023

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Abstract

Occupational health often faces challenges from musculoskeletal issues, especially among workers involved in physically demanding tasks. Addressing this concern, our study centres on the creation of an elbow-supporting exoskeleton, outfitted with Dynamixel 106 motors and managed via a Raspberry Pi 4 using ROS Melodic. Utilising an impedance controller, the apparatus has achieved a Root Mean Square Error (RMSE) value of 0.352, indicating effective torque control between the anticipated and actual motor outputs. User evaluations, facilitated by Inertial Measurement Units (IMU) and Electromyography (EMG) sensors, were principally conducted through the bicep curl exercise. Initial outcomes suggest a significant 50% reduction in mean muscle exertion, as measured via EMG, thereby underscoring the device's efficacy in diminishing muscle strain. As a result, the research offers persuasive, data-backed substantiation that endorses the exoskeleton's utility as a proactive safeguard to mitigate the risk of developing MSDs.

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1 Introduction

Musculoskeletal Disorders (MSD) persist as a paramount concern within the sphere of occupational well-being, especially for individuals immersed in manual tasks. These ailments, often marked by discomfort, pain, and physical hindrances, predominantly stem from repetitive actions, undue strain, and extended static positions. According to a report by the U.S. Bureau of Labor Statistics, MSDs accounted for approximately 33% of all worker injury and illness cases in 2019 [1]. The ramifications of MSDs are extensive, encompassing diminished work output, increased instances of absenteeism, and heightened healthcare costs [2]. The economic impact is also substantial; the Occupational Safety and Health Administration (OSHA) estimates that MSDs cost employers in the United States about $20 billion annually in workers' compensation costs alone [3]. As the global workforce confronts these challenges, there's an intensified drive to unearth innovative measures to alleviate the risks tied to MSDs.

In this milieu, wearable exoskeletons have surfaced as a potential beacon of hope. These apparatuses, akin to external wearable suits, are crafted to seamlessly integrate with the human physique, offering support, amplifying strength, and curtailing muscle weariness. The prospective advantages of exoskeletons span from bolstered worker safety and reduced injury occurrences to augmented efficiency and work output [4].

The elbow, given its central role in hoisting and a myriad of manual activities, has been spotlighted as a crucial focal point. Existing exoskeletons have shown promise in augmenting human capabilities and reducing muscle strain [5], [6]. However, they often come with limitations such as bulkiness, limited range of motion, and high costs [7]. Some also lack the adaptability to cater to individual user needs, making them less versatile in real-world applications [8]. These obstacles highlight the pressing demand for an approach that is tailored to individual users, offers greater flexibility, and is economically viable. Acknowledging these requirements, the present research undertook the mission of designing and developing an elbow-focused exoskeleton. Energized by Dynamixel 106 motors and orchestrated by control mechanisms, this exoskeleton stands as a testament to precision, adaptability, and a design ethos centered around the user [9].

It's of utmost importance to corroborate the exoskeleton's efficacy in tangible, real-world settings for which an evaluation strategy was adopted, harnessing the capabilities of Inertial Measurement Units (IMU) and Electromyography (EMG) sensors. These instruments not only shed light on the mechanical ramifications of the exoskeleton but also probed its physiological impacts, furnishing a comprehensive view of its potential boons and areas warranting refinement [10].

The wider repercussions of this investigation ripple beyond the immediate confines of occupational health. As industries across the globe aspire for heightened efficiency and safeguarding measures, the revelations of this study hold resonance for decision-makers, industry trailblazers, healthcare professionals, and the broader working populace. Furthermore, in an era where technological advancements are ceaseless, it's imperative to channel this momentum in ways that underscore human welfare and ergonomic integrity [11].

In the backdrop of the aforementioned, this study endeavours to furnish a comprehensive perspective on the challenges ushered in by MSDs, delve into the promise held by wearable exoskeletons, and pave the way for future explorations in this arena.

1.0.1 Aim

This project aims to develop an occupational upper-limb exoskeleton specifically targeting the elbow joint to assist workers in lifting heavy objects, focusing on mechatronic design, control, physical and sensor interface design, and user testing.

1.0.2 Objectives

1. To investigate the present state of the art on upper limb exoskeletons and their possible impact on physical exposures and worker performance.

2. Develop a wearable elbow exoskeleton that can assist workers in performing heavy lifting tasks.

3. Integrate a range of sensors, including EMG and IMU, to record and analyse data related to the user's muscle activity, joint angles and EMG signal parameters during exoskeleton use.

4. Conduct user testing with diverse individuals, to assess the exoskeleton's impact on lifting capacity, user comfort, and overall performance.

1.0.3 Project Management

The project initiation was marked by a Design Analysis phase where the exoskeleton's requirements were studied and design parameters established based on a literature review Appendix:I. This paved the way for the Designing stage, utilizing CAD software for the architectural blueprint. 3D Printing was the subsequent step, converting design plans into tangible components. Assembly followed, focusing on the evaluation and adjustment of these 3D printed parts. Concurrently, ROS Implementation was carried out to facilitate the exoskeleton's interaction with the Robot Operating System.

The Testing stage was conducted to validate the exoskeleton's functionalities, accompanied by the development of Protocols to delineate user testing procedures. Ethical Approval in appendix:M was then secured, ensuring compliance with ethical standards. User Recruitment was undertaken, followed by the Prepare for Experimentation stage, where the setup was readied for user tests. The Data Analysis phase concluded the project, involving statistical scrutiny of the collected data Appendix:J.

In terms of project management, a Gantt chart was instrumental in dictating the project timeline and resource allocation, and was often reviewed during weekly meetings with the supervisor Appendix:I. These meetings served as checkpoints for progress evaluation and timeline adjustments. Communication was maintained among all stakeholders, which proved crucial for meeting deadlines and managing resources. Although guided by a supervisor, the project was chiefly led by me, emphasizing my autonomous management and decision-making skills.

Risk management was a key concern, with a comprehensive risk assessment performed at the outset Appendix:J. Identified risks, such as hardware malfunctions and safety hazards, were mitigated through control measures, thus contributing to the project's overall success.

2 Literature Review

2.1 Methodology for Literature Review

Comprehensive searches were conducted on databases such as PubMed, IEEE Xplore, ScienceDirect, and Google Scholar using keywords like "elbow exoskeleton", "exoskeleton control mechanisms", "user testing of exoskeletons", and related terms. Initial screening was done based on titles and abstracts to filter out irrelevant articles. Articles passing the initial screening underwent a full-text review to determine their relevance based on the inclusion and exclusion criteria. Relevant data, such as study objectives, methodologies, findings, and conclusions, were extracted from the selected articles. The quality and reliability of the selected articles were assessed based on their methodologies, sample sizes, statistical analyses, and the journals in which they were published. A total of 26 papers were selected for the literature review, providing a comprehensive overview of various exoskeletons and exosuits, their features, advantages, limitations, and applications. The extracted data were synthesised to draw patterns, comparisons, and contrasts, which formed the foundation of the literature review. Given the dynamic nature of technological research, the literature review was periodically updated to include new findings and advancements in the field.

2.2 Inclusion Criteria

1. **Relevance to the Study:** Only articles directly related to elbow exoskeletons, their design, control mechanisms, and user testing were considered.

2. **Publication Date:** Articles published within the last ten years were prioritised to ensure the most recent and relevant technological advancements were included.

3. **Peer-Reviewed Journals:** To ensure the quality and reliability of the data, only articles from peer-reviewed journals were included.

4. **Language:** Articles published in English were considered to ensure a comprehensive understanding and analysis.

5. **Availability:** Full-text articles that were accessible and not behind paywalls were included.

6. **Study Type:** Both qualitative and quantitative studies were considered, with a preference for experimental and observational studies.

2.3 Exclusion Criteria

1. **Off-topic:** Articles that did not directly address elbow exoskeletons or their associated components were excluded.

2. **Outdated Technologies:** Studies focusing on technologies or methodologies that have been rendered obsolete were excluded.

3. **Non-Peer Reviewed:** Articles from non-peer-reviewed sources, such as blogs or opinion pieces, were excluded.

4. **Incomplete Data:** Studies with incomplete datasets or missing crucial information were not considered.

5. **Language Barrier:** Articles not available in English, and for which reliable translations were not accessible, were excluded.

2.4 Exoskeletons/Exosuits developed for lifting tasks

Exo4Work, this exoskeleton offers six degrees of freedom and focuses on passive actuation, specifically targeting the shoulder joint [12], [13]. It employs a passive Remote Actuation System (pRAS) and provides a torque of 9 Nm, making it suitable for lifting tasks and overhead works. However, being passive, it may lack the dynamic adaptability that active systems offer Appendix:K.

Exo-Jacket 2.0 takes a hybrid approach with nine degrees of freedom, two of which are active [14]. It uses an electric motor and gearbox for actuation, focusing on both the shoulder and elbow joints. With a torque of 40 Nm, it is designed for lifting and carrying heavy objects. The hybrid nature allows for more flexibility but may add complexity to the control systems Appendix:K.

The lightweight active upper extremity exoskeleton is an exosuit with a single degree of freedom, focusing solely on the elbow joint [15]. It employs a Soft Pneumatic actuator and provides a torque of 16.7 Nm. Its lightweight and focused design make it ideal for lifting heavy objects, but it may not offer comprehensive support for multiple joints.

Another noteworthy device is the cable-driven soft exosuit, which offers nine degrees of freedom and employs a Bowden cable actuator. It focuses on the elbow and fingers, providing a torque of 4.45 Nm. While it offers support for intricate tasks, the cable-driven system may require regular maintenance Appendix:K.

The Upper limb hybrid exoskeleton offers two degrees of freedom, one passive for the shoulder and one active for the elbow [16]. It employs extension springs and an electric motor, providing different torque levels for different joints. This exoskeleton is designed for overhead industrial tasks and elevation tasks, but its hybrid nature might complicate its operation.

The diverse range of exoskeletons and exosuits, each with its unique set of advantages and limitations. While some focus on passive actuation for specific joints, others employ hybrid or active systems for more dynamic support. The choice between these systems often involves a trade-off between complexity, maintenance, and adaptability [12], [14]–[16].

2.5 A Review of Hardware Technologies in Occupational Exoskeletons

The field of wearable exoskeletons has witnessed significant advancements over the past few decades. One of the primary motivations behind the development of occupational exoskeletons is the increasing prevalence of musculoskeletal diseases (MSDs), which are a leading cause of work absence [17]. In Germany alone, MSDs account for 21.9% of work absences, translating to approximately 125 million days annually [17]. Occupational exoskeletons, especially passive ones, have shown promise in reducing fatigue and the risk of injuries during manual [18]. However, achieving a reliable and efficient automatic support control remains a challenge [19].

Human performance in tasks such as holding and carrying loads is inherently limited due to factors like maximum muscle force and the onset of fatigue [20]. Fatigue can lead to quicker muscle fatigue, reducing the duration for which a load can be held or carried [20]. Occupational hazards associated with manual load handling have been identified in various professions, including nursing aides, craft workers, machine operators, and construction workers [21]. Exoskeletons, both passive and active, have been developed for various purposes, including assisting with lifting, lowering, holding, or carrying objects, as well as for rehabilitation [21].

The development of assistive robots has been a focal point since the late 1960s, aiming to aid patients affected by neuromuscular disorders [22]. Traditional rigid exoskeletons face challenges in terms of portability, safety, ergonomics, autonomy, and cost [22]. A significant challenge with traditional exoskeletons is the kinematic constraints they impose on the wearer's joints [23]. Misalignment between the robot's and the human's joints can lead to hyperstaticity, which disrupts the natural kinematics of human movements [23]. A recent paradigm in this field involves the use of soft, clothing-like frames, known as exosuits [24]. Exosuits offer several advantages, such as compliance, low profile, and minimal inertia, making them suitable for daily use [24].

Soft robotics has emerged as a promising field in human motion assistance, envisioning a future where robotic devices seamlessly integrate into our daily lives to restore or augment human performance [25]. The use of fabric and elastomers in place of rigid links offers advantages such as reduced weight, smaller dimensions, and lower power consumption, making these devices more practical for everyday use [25]. Soft exoskeletons, often referred to as "exosuits," have shown significant potential in both enhancing performance and compensating for neuromuscular deficiencies [26]. Most existing wearable exoskeletons consist of rigid links that work in parallel with human limbs [27]. However, these rigid exoskeletons come with challenges like large structure dimensions, heavy weight, high energy consumption, and potential misalignment between robot and human joints [28].

The domain of soft wearable robotics, particularly exosuits, is an emerging field that offers innovative solutions with potential applications in various sectors [29]. The use of materials like textiles and elastomers in exosuits ensures compatibility with intricate human biomechanics [30]. Unlike rigid exoskeletons, exosuits do not present kinematic incompatibility issues with human joints [30].

Soft-type exoskeletons, made of materials like textiles or leathers, interface with the human body and use the biological skeletal structure to bear compressive loads [31]. The driving torques are applied to human joints via tensile forces, parallel to muscles [31]. Soft exoskeletons, devoid of rigid joints and links, eliminate the joint misalignment problem [31]. Neural networks, with their inherent ability for nonlinearity approximation and pattern recognition, have been widely applied in the control of rehabilitation robots. They offer potential advantages in enhancing biological joint torque estimation during robot-assisted training [31].

2.5.1 A Review of Control System Technologies in Exoskeletons

Traditional rigid exoskeletons often employ control algorithms that can impose kinematic constraints, leading to issues such as hyperstaticity that disrupt natural human movements [32], [33]. This has led to the exploration of more adaptive control systems, particularly in the emerging domain of soft robotics and exosuits [34].

One comprehensive survey offers an in-depth exploration of variable impedance control (VIC) in robotics [35]. The authors emphasise the importance of VIC in robots that interact with dynamic and uncertain environments, including scenarios involving human-robot interaction. They point out that VIC offers advantages over constant impedance control, particularly in dynamic environments. Impedance control is also crucial for ensuring safe and efficient human-robot interactions. However, challenges exist in ensuring the stability of VIC systems, especially when interacting with unknown environmental dynamics.

Neural networks have been integrated into the control systems of rehabilitation robots, showing promise in personalized therapy [36]. These networks are capable of nonlinearity approximation and pattern recognition, enhancing biological joint torque estimation during robot-assisted training [37]. Such advancements are crucial for providing the right amount of assistance at the optimal time, thereby maximizing therapeutic benefits [38].

In industrial settings, where the risk of musculoskeletal injuries is high, the control systems of exosuits aim to provide dynamic support. This enables workers to perform tasks with reduced physical strain, especially in jobs requiring repetitive motions or heavy lifting [39]. The economic implications of these advancements are significant, potentially leading to reduced healthcare costs and increased productivity [40].

The challenge of achieving reliable and efficient automatic support control remains an area for further research [19]. The control system's adaptability and responsiveness are paramount, especially in occupational settings where quick and precise movements are often required. Therefore, the current study focuses on developing a control system that is not only precise and adaptable but also user-centric, aiming to mitigate the limitations observed in existing systems.

2.5.2 A Review of User Study in Exoskeletons

The growing issue of musculoskeletal disorders (MSDs) in the workplace has accelerated the need for effective wearable exoskeletons, a point strongly emphasized in existing studies [17]. These disorders are a major contributor to employee absenteeism, thereby necessitating innovative solutions [17].

Different types of exoskeletons, both of the rigid and soft varieties, have been engineered to aid in activities like lifting, holding, and lowering objects [21]. However, existing literature points out that conventional rigid exoskeletons are plagued by issues such as limited portability, safety concerns, and restrictions in natural movement [22], [23]. Soft exoskeletons, commonly known as exosuits, have been introduced as an alternative, offering benefits like adaptability and a less intrusive design [24], [25].

To gauge the effectiveness of these wearable devices, user testing often employs a dual-method approach, utilizing Inertial Measurement Units (IMU) and Electromyography (EMG) sensors [10]. This dual-method approach is crucial for determining the device's compatibility with human biomechanics and its efficacy in alleviating muscle fatigue and strain [20], [26].

Existing research also underscores the potential of personalized treatment plans in rehabilitation robotics, made possible through the incorporation of neural networks [36], [37]. These technological advancements are particularly pertinent to our study as they offer valuable perspectives on how to maximize the therapeutic advantages of exoskeletons [38].

While progress has been made, there are still hurdles to overcome, especially concerning the limitations in movement imposed by traditional rigid exoskeletons [32]. Soft exoskeletons have been designed to address these limitations, allowing for a more natural interaction between the device and the human body [34].

3 Research Methodology

3.1 Hardware

The primary motivation behind such endeavours is the potential to reduce the risk of musculoskeletal disorders (MSDs) and enhance human performance in manual tasks [41]. The elbow joint, being a hinge joint, plays a pivotal role in lifting tasks. Its biomechanical structure and function make it susceptible to strain during repetitive or heavy lifting tasks [42]. By targeting this joint, our exoskeleton aims to provide support where it's most needed, potentially reducing the risk of injuries like tennis elbow or other strain-induced conditions.

Our hardware design, while innovative, draws inspiration from existing research. The emphasis on a cable-driven mechanism ensures flexibility and lightweight operation, crucial for wearable robotics [43]. Furthermore, the integration of advanced motors with a versatile computing platform like Raspberry Pi signifies a blend of power and precision, aiming to offer users a balance between support and freedom of movement.

The hardware design and development phase was pivotal in ensuring the efficacy and reliability of the exoskeleton. This section elucidates the systematic approach adopted for the hardware design, highlighting the rationale behind each choice.

3.1.1 Dynamixel 106 Motors:

The development of the exoskeleton necessitated the selection of motors that could seamlessly align with the project's objectives, ensuring a balance between power, precision, and user comfort. The Dynamixel 106 motors Figure:3.1 emerged as the optimal choice, driven by a combination of their technical specifications and the demands of the exoskeleton application. Renowned for

Figure 3.1: Dynamixel MX-106

their impressive torque output, these motors can deliver a
stall torque of approximately 8.4 Nm at 12V and 10.2 Nm at 14.8V. Such high torque ensures the exoskeleton's capability to provide adequate force assistance during strenuous activities like lifting.

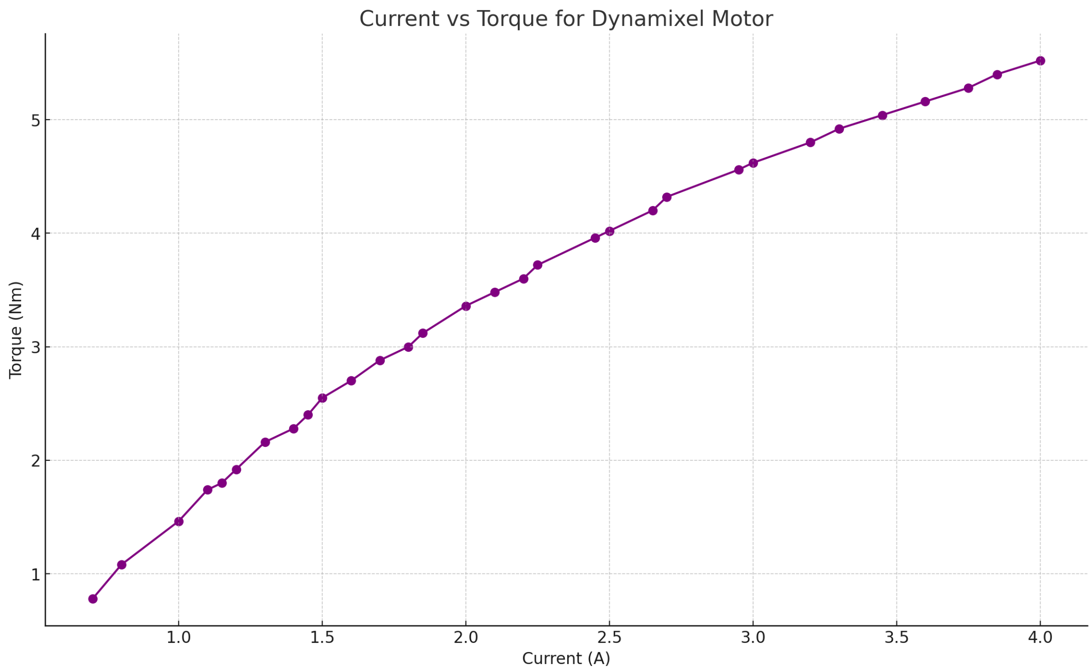

Figure 3.2: Dynamixel 106 current v/s torque characteristics curve

The figure:3.2 represents a linear relationship between current and torque enabling a highly predictable motor response. This is essential for impedance control strategies, where precise motor behaviour is crucial for achieving the desired mechanical impedance. Additionally, the motor exhibits a broad operating range, offering a torque output that spans from 0.78 Nm at 0.7 A to 5.52 Nm at 4 A. This range accommodates various levels of assistance or resistance within the exoskeleton, making it adaptable to a multitude of tasks.

Furthermore, the precision offered by the Dynamixel 106 motors, with a resolution of 0.088 degrees, is pivotal. This precision ensures the exoskeleton's movements are fine-tuned, mimicking natural human motions and preventing any discomfort or strain to the user. Their compact design, measuring 40.3 mm x 65.1 mm x 46 mm, and lightweight nature, weighing approximately 153g, further enhance user comfort. Such design considerations ensure the exoskeleton remains non-intrusive, promoting user mobility without adding unnecessary bulk or weight.

Integration capabilities were another significant factor in the motor selection. The Dynamixel

106 motors' versatility, equipped with communication options like TTL and RS-485, facilitates seamless integration with diverse control systems. This was especially crucial given the custom control system developed for the exoskeleton. Moreover, the motors' reputation for durability and reliability ensures the exoskeleton's longevity, reducing the need for frequent maintenance or replacements. In essence, the incorporation of the Dynamixel 106 motors into the exoskeleton design was a strategic decision, ensuring the device's efficacy and user-friendliness [44].

3.1.2 Exoskeleton Design

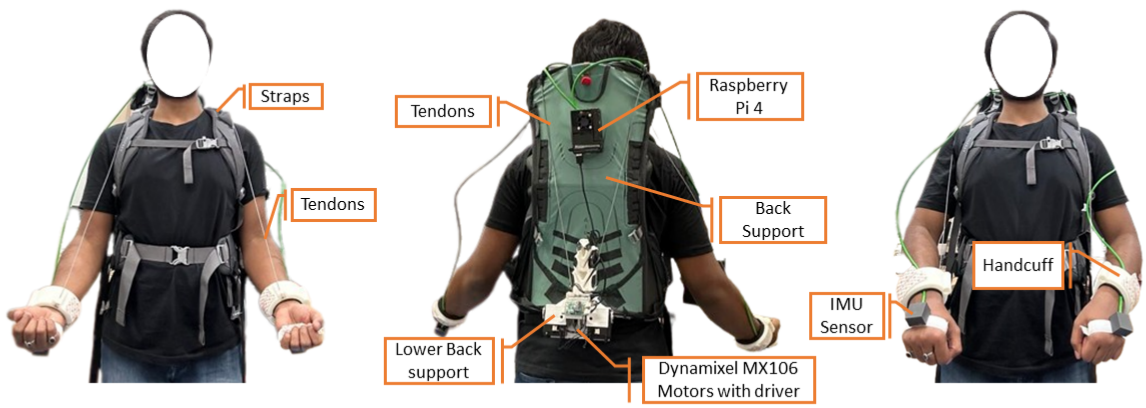

Figure 3.3: The Upper-limb Exoskeleton

The exoskeleton's design was a culmination of meticulous planning and engineering, with a primary focus on the elbow joint. This specificity was crucial to ensure that the device provided targeted support, enhancing the user's lifting capabilities while preserving the natural range of motion of the arm figure:3.3.

Ergonomics played a pivotal role in the design process. The exoskeleton was crafted to contour seamlessly to the user's body, ensuring maximum comfort during prolonged usage. This ergonomic design not only reduced the chances of strain or discomfort but also ensured that the user could wear the exoskeleton for extended periods without fatigue.

A significant feature of the exoskeleton was its cable-driven system. This system utilized the high torque output of the Dynamixel 106 motors, which were strategically placed at the lower back of the user. These motors interfaced with a series of pulleys, translating the motor's rotational motion into linear motion that provided the necessary force assistance at the elbow joint. This cable-driven mechanism ensured smooth and synchronized movement, closely mimicking the natural biomechanics of the human arm.

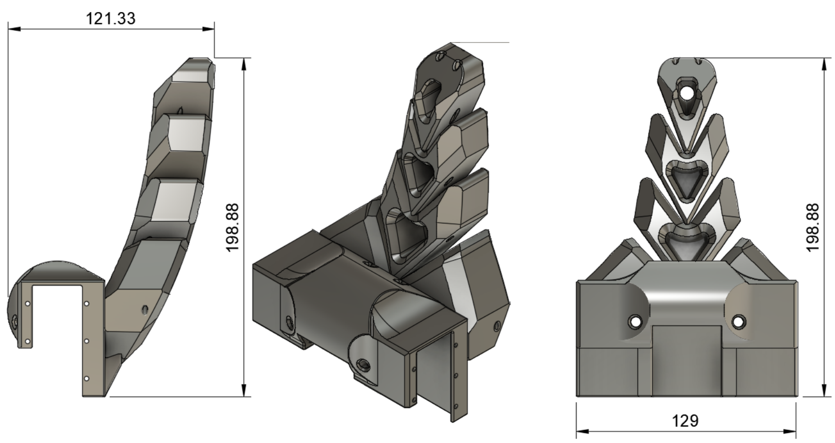

Figure 3.4: Back Support and Motor Housing

To house the Dynamixel motors and the associated pulley system, a robust support structure figure:3.4 was integrated into a trekking backpack. This backpack was chosen for its inherent durability and comfort features. To further enhance its sturdiness, metal linings were fixed readily in the backpack, ensuring that the backpack could withstand the mechanical stresses exerted by the motors and pulleys. The metal-reinforced backpack not only provided a stable platform for the exoskeleton's hardware but also distributed the system's weight evenly across the user's back, preventing any localized pressure points.

3.1.3 Sensor Integration

The integration of the BNO055 Adafruit 9-axis Inertial Measurement Unit (IMU) figure:3.5 into the exoskeleton design was aimed at enhancing its responsiveness and adaptability. Positioned at the wrist, this IMU was pivotal in capturing a comprehensive set of data related to the user's arm movement. The BNO055 is a sophisticated sensor that combines a triaxial 16-bit gyroscope, triaxial

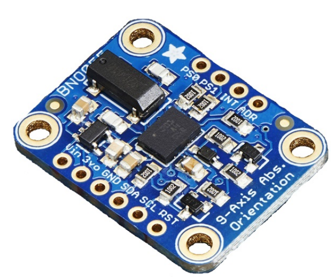

Figure 3.5: Adafruit BNO005 (9-axis IMU)

14-bit accelerometer, and a triaxial geomagnetic sensor. This combination allows the IMU to measure both angular velocity and acceleration, offering a detailed understanding of both the position and motion of the user's arm.

Several factors underscored the choice of the BNO055 for this application. Firstly, the BNO055 offers high accuracy in measurement, ensuring that the data captured is reliable. This precision is crucial for an exoskeleton, where even slight deviations can lead to misalignment or discomfort. Additionally, the sensor comes with an onboard processor, enabling it to compute the orientation data in real-time [45]. This feature not only reduces the computational load on the primary control system but also ensures swift responsiveness. Its compact design ensures that it doesn't add bulk to the exoskeleton, and its power efficiency means it doesn't drain the system's battery rapidly. Furthermore, the data from the IMU can be seamlessly integrated with the control algorithms, ensuring that the motors actuate in harmony with the user's natural movements. This synchronization is vital for ensuring that the exoskeleton feels like a natural extension of the user's body.

The hardware was equipped with data logging capabilities, allowing for the continuous collection of data during user testing. This data was then analysed to assess the exoskeleton's performance, identify areas of improvement, and validate the initial design choices.

Our hardware design, while innovative, draws inspiration from existing research. The emphasis on a cable-driven mechanism ensures flexibility and lightweight operation, crucial for wearable robotics [43]. Furthermore, the integration of advanced motors with a versatile computing platform like Raspberry Pi signifies a blend of power and precision, aiming to offer users a balance between support and freedom of movement.

While our hardware design boasts several advancements, it's essential to acknowledge its limitations. The cable-driven mechanism, though lightweight, might face wear and tear over extended usage. Additionally, the reliance on a single computing unit (Raspberry Pi 4) could pose challenges in multitasking, especially when integrating future sensors or expanding the exoskeleton's capabilities.

Several exoskeletons in the market and research focus on full-arm support or even full-body assistance [46]. Our choice to target only the elbow joint is both a limitation and a strength. While it offers specialized support for lifting tasks, it might not provide comprehensive protection against MSDs affecting other parts of the arm.

3.2 Control System

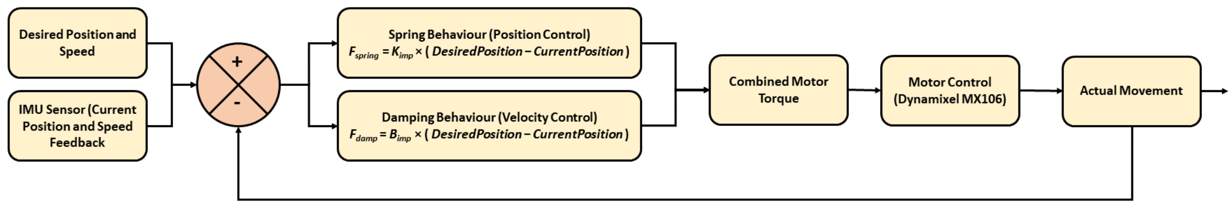

Figure 3.6: Control System block diagram

The control system of an exoskeleton plays a pivotal role in ensuring its effectiveness, safety, and adaptability. The choice of control strategy can significantly influence the exoskeleton's performance, especially in dynamic environments where user intentions and external disturbances constantly vary. In the realm of exoskeleton design, the control system is not just about actuating motors; it's about ensuring a harmonious interaction between the human user and the robotic system.

Impedance control in the figure:3.6 has emerged as a preferred control strategy for many robotic applications, especially in human-robot interaction scenarios1. The primary reason for its popularity is its ability to model the dynamic interaction between the robot and its environment using virtual components like springs and dampers [47]. This approach ensures that the system doesn't rigidly follow a set trajectory but adapts its behaviour based on encountered disturbances, ensuring smooth and safe interactions.

For exoskeletons, especially those designed for the upper limb, the impedance control strategy offers several advantages. Firstly, it ensures that the exoskeleton is responsive to the user's intentions. For instance, when a user tries to lift an object, the system can detect the user's effort through the positional error and actuate the motors to provide the necessary assistance [48]. Secondly, the damping behaviour ensures that the system converges smoothly to the desired state without excessive oscillations, which is crucial for tasks that require precision.

Impedance control establishes a dynamic relationship between the force exerted by the robot and its motion. The overarching goal is to emulate the behaviour of a passive mechanical impedance, typically modelled using mass, damper, and spring elements [49].

3.2.1 Mechanical Impedance

Mechanical impedance, Z, quantifies a system's response to external forces. For a one-dimensional linear system, it's mathematically expressed as [49], [50]:

$$Z(s) = \frac{F(s)}{V(s)} \tag{3.1}$$

Where:

- $F(s)$ is the Laplace transform of the force.
- $V(s)$ represents the Laplace transform of the velocity.

3.2.2 Spring Behavior (Position Control)

The spring component simulates the system's response to positional deviations. According to Hooke's law for a linear spring [50]:

$$F_{spring} = -K \times \Delta x \tag{3.2}$$

Where:

- F_{spring} is the force exerted by the spring.
- K denotes the spring constant.
- Δx signifies the displacement from the equilibrium position.

Incorporating the provided equation, the force exerted by the virtual spring, in response to positional errors, is given by:

$$F_{spring} = K_{imp} \times (DesiredPosition - CurrentPosition) \tag{3.3}$$

3.2.3 Spring Behavior (Position Control)

The spring component simulates the system's response to positional deviations. According to Hooke's law for a linear spring [50]:

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- K denotes the spring constant.
- Δx signifies the displacement from the equilibrium position.

Incorporating the provided equation, the force exerted by the virtual spring, in response to positional errors, is given by:

$$F_{spring} = K_{imp} \times (DesiredPosition - CurrentPosition) \tag{3.5}$$

3.2.4 Damping Behavior (Velocity Control)

Damping ensures the system's smooth convergence to its desired state. For a linear damper, the force is proportional to velocity [50]:

$$F_{damp} = -B \times \Delta v \tag{3.6}$$

Where:

- F_{damp} denotes the damping force.
- B is the damping coefficient.
- Δv represents the velocity.

Using the provided equation, the damping force, based on velocity errors, is:

$$F_{damp} = B_{imp} \times (DesiredSpeed - CurrentSpeed) \tag{3.7}$$

The total force exerted by the system is a summation of the spring and damping forces:

$$F_{total} = F_{spring} + F_{damp} \tag{3.8}$$

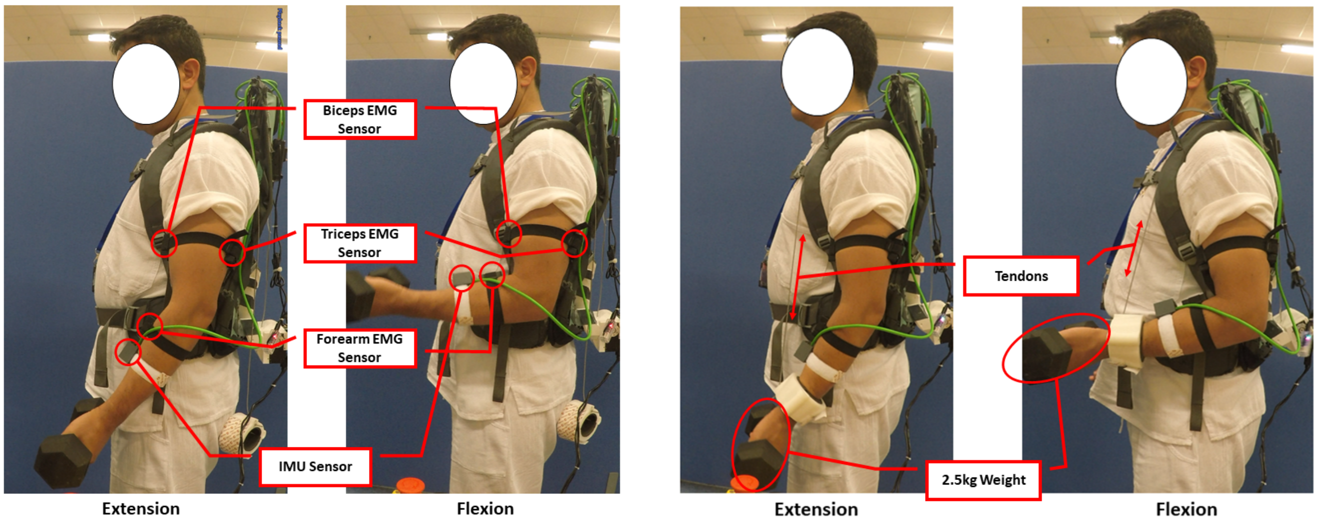
$$F_{total} = -K \times \Delta x - B \times \Delta v \tag{3.9}$$

This equation encapsulates the desired force based on both position and velocity errors and can be represented using the block diagram figure: 3.6.

The Impedance Control strategy, grounded in classical mechanics, offers an adaptive control mechanism for our exoskeleton. By judiciously selecting the parameters K and B, as well as their impedance counterparts K_{imp} and B_{imp}, the exoskeleton's behaviour can be meticulously calibrated, ensuring responsiveness to user intentions and safety during interactions. For this study the values for K_{imp} and B_{imp} were selected using hit and trial method and the most optimised values were found to be $K_{imp} = 3.9$ and $B_{imp} = 0.8$.

While the impedance control strategy offers numerous advantages, it's essential to recognize its limitations. The effectiveness of this control strategy is highly dependent on the accurate tuning of the stiffness and damping coefficients [51]. Incorrect tuning can lead to unstable system behaviour or reduced performance. Moreover, the strategy assumes a linear relationship between position and force, which might not always hold true in complex real-world scenarios.

3.3 User Testing



(a) User Testing without Exoskeleton

(b) User Testing with Exoskeleton

Figure 3.7: User Testing with and without Exoskeleton

The human body has its limitations such as the endurance and strength of our muscles, especially during repetitive tasks. Musculoskeletal disorders (MSDs) are a significant concern in occupational settings, with the upper limb being particularly susceptible. The elbow joint, being a pivotal point of the upper limb, plays a crucial role in many lifting tasks. The study aimed to evaluate the effectiveness of an elbow exoskeleton in assisting manual lifting tasks, with a focus on reducing muscle fatigue and strain.

One of the objectives was to assess the efficacy of the elbow exoskeleton in augmenting force during manual lifting tasks. By gauging its influence on muscle activity, the study endeavoured to ascertain the exoskeleton's potential to mitigate muscle fatigue and strain.

The bicep curl is a fundamental movement that isolates the bicep muscle, making it an ideal exercise to evaluate the effectiveness of our exoskeleton. The bicep curl primarily involves flexion at the elbow joint, which directly aligns with the exoskeleton's design focus. By choosing this movement, we ensured that the exoskeleton's assistance was targeted and measurable. Moreover, the bicep curl is a standard exercise in both rehabilitation and strength training, making our findings relevant to a broader audience [52].

The user testing represented in figures:3.7a and 3.7b transpired at the Bristol Robotics Lab and the research was a collaborative effort between the University of Bristol and the University of the West of England and the user study protocol was designed and the protocol can be viewed in Appendix A.

3.3.1 Participant Recruitment and Consent

The process of participant selection was done ensuring a diverse and representative sample for the study. To begin with, a random selection method was employed, drawing from a pool of volunteers who had expressed interest in participating in research studies. This method was chosen to minimize any selection bias and ensure that the study's findings could be generalized to a broader population.

Once the initial pool was established, further stratification was done based on gender and age groups (19 yrs - 40 yrs). The aim was to ensure a balanced representation across different demographics, recognizing that muscle activity and response to exoskeletal assistance might vary across these groups. This stratified random sampling ensured that the study's findings would be robust and widely applicable. The demographic data for the user study can be viewed in Appendix F.

Special attention was also given to the health status of the participants. Only individuals who identified as healthy, without any recent history of musculoskeletal disorders or injuries, were considered. This criterion was essential to ensure that the baseline muscle activity data would not be skewed by any underlying health conditions.

Upon finalizing the list of participants, the next step was obtaining informed consent. Each participant was presented with a comprehensive consent form that detailed the study's objectives, the methods to be employed, potential risks, and the measures in place to mitigate those risks. The form was designed to be transparent and thorough, ensuring that participants had all the information they needed to make an informed decision. To further ensure understanding, participants were encouraged to ask questions and seek clarifications on any aspect of the study. Only once they demonstrated a clear understanding and voluntarily agreed to participate were they formally enrolled in the study.

This rigorous participant selection and consent process underscored the research team's commitment to ethical research practices, ensuring that the study's findings would be both valid and ethically sound. The consent and information document can be viewed in the Appendix B, C.

3.3.2 Maximum Voluntary Contraction

Maximum Voluntary Contraction (MVC) stands as a metric, denoting the zenith of force a muscle can produce during a single, unassisted contraction. Prior to the commencement of the primary experimental tasks, participants were guided to exert the utmost force they could muster, facilitating the acquisition of this MVC data. This data acts as a reference point or a standard against which other muscle activity readings can be placed.

The significance of capturing MVC data lies in its ability to provide a context. When EMG readings from various tasks are normalized against the MVC values, it offers a clearer perspective on the relative exertion or load on the muscles. Such a comparison becomes invaluable, especially when assessing the muscle's operational efficiency and the levels of strain during different activities. In the context of this study, contrasting the EMG data from bicep curls against the MVC values illuminated the muscle's performance metrics when aided by the exoskeleton versus an unassisted scenario. The process followed for MVC for this study can be found in the protocol which can be viewed in Appendix A.

3.3.3 Data Collection Procedure

The data collection process was a critical component of the study, designed to capture precise and actionable insights into muscle activity when using the exoskeleton. To ensure the accuracy and reliability of the data, the process was meticulously planned and executed.

Electromyographic (EMG) sensors [53] were placed on the participants' biceps brachii muscles. The placement was chosen due to the biceps brachii being the primary muscle group involved in elbow flexion, which is the main movement during a bicep curl. Proper placement ensured that the sensors would capture the electrical activity of the muscle fibers during contraction and relaxation phases [54].

Once the sensors were in place, participants were instructed to perform three sets of bicep curls with 2.5kg (5.5lb) dumbbell as represented in figures:3.7a and 3.7b. Each set consisted of a series of controlled movements, with a 30-second break between sets to minimize muscle fatigue. This exercise regimen was chosen to simulate a typical weightlifting routine, allowing for a realistic assessment of the exoskeleton's impact on muscle activity.

The study was divided into two sessions for each participant. In the first session, participants performed the bicep curls without the exoskeleton, serving as a control group figure:3.7a. In the second session, participants repeated the exercise, this time equipped with the exoskeleton figure:3.7b. This design allowed for a direct comparison of muscle activity with and without exoskeletal assistance.

Before the main exercise sessions, participants were subjected to a Maximum Voluntary Contraction (MVC) test. MVC is a widely recognized measure used to determine the maximum force a muscle can exert during a contraction [55].

The video of the user study can be found in the link [56].

Variables

1. **Independent Variables:**
   (a) **Use of Exoskeleton:** This is a primary independent variable, as the research often compares outcomes with and without the use of the exoskeleton.

   (b) **Control Strategy (Impedance Control):** The type of control strategy employed can influence the performance and interaction of the exoskeleton with the user.

   (c) **Type of Task (Bicep Curl):** The specific task or movement being performed by the user can influence the results, especially when assessing muscle activity.

   (d) **Sensor Type (EMG, IMU):** Different sensors might provide different feedback, influencing the control and performance of the exoskeleton.

2. **Dependent Variables:**
   (a) **Muscle Activity:** Measured using EMG sensors, this variable provides insights into how muscles respond under different conditions (with and without the exoskeleton).

   (b) **Muscle Fatigue:** A derivative of muscle activity, fatigue levels can be inferred from prolonged or intense muscle activity.

(c) **Performance Metrics:** This could include the accuracy or efficiency of task completion, speed, or any other performance-related metric.

(d) **Safety and Comfort:** While not explicitly measured, the safety and comfort of the user when using the exoskeleton can be considered a dependent variable, especially when evaluating the exoskeleton's design and control strategy.

3.3.4 Pre-Experiment Questionnaire

Before starting the experimental journey, it was essential to gather a comprehensive understanding of the participants' backgrounds and physical conditions. To this end, a pre-experiment questionnaire was administered to all participants. This instrument was not a formality but played a pivotal role in ensuring the integrity and relevance of the study's findings.

The questionnaire was structured to capture a spectrum of demographic details, ranging from age and gender to educational qualifications. Such data provided a contextual backdrop, enabling a nuanced interpretation of results, especially when considering potential correlations or patterns that might emerge relative to these demographic factors.

Beyond demographics, the questionnaire delved deeper, probing into the participants' physical health, specifically focusing on the left upper limb. By inquiring about the frequency of exercise and any history or presence of musculoskeletal discomfort in the left arm, the study aimed to filter out any external variables that might skew the results. For instance, a participant with a pre-existing ailment might exhibit different muscle activity patterns, which, if not accounted for, could lead to misleading conclusions.

Furthermore, the emphasis on the left upper limb was not arbitrary. Given that the exoskeleton's design was tailored for the left elbow joint, understanding the health and condition of this specific limb was paramount. Any anomalies or discomforts could potentially influence the participant's interaction with the exoskeleton, thereby affecting the EMG readings. The questionnaire can be viewed in Appendix D.

3.3.5 Post-Experiment Satisfaction Survey

Upon the culmination of the experimental tasks, participants were introduced a satisfaction survey, designed to get insights into their experience with the exoskeleton. This survey was an integral component of the research, aimed at understanding the user's perspective, which is paramount in the development and refinement of wearable assistive devices.

The survey encompassed several pivotal dimensions. Firstly, it probed into the exoskeleton's weight—a critical factor as an overly cumbersome device could negate its benefits. The adjustability of the exoskeleton was another focal point, given that a one-size-fits-all approach seldom suffices in wearable technology. Participants were also queried about the device's safety protocols, a paramount concern to ensure that users are shielded from potential harm during operation.

Furthermore, the survey delved into the user-friendliness of the exoskeleton. While a device might be technologically advanced, it loses its efficacy if users find it daunting or counterintuitive. Lastly, the overarching comfort while donning the exoskeleton was assessed, encompassing aspects like fit, ease of movement, and any pressure points or areas of discomfort.

This post-experiment questionnaire, thus, served as a bridge between the empirical data gleaned from the tests and the subjective experiences of the participants. The research aimed to present a comprehensive overview of the exoskeleton's potential and areas of improvement. The questionnaire can be viewed in Appendix E.

3.3.6 Data Processing and Analysis

The analysis of the captured data is to derive meaningful insights from the study. Each step in the data processing and analysis was carefully chosen based on its relevance and significance in the context of the study.

(a) Filtering: EMG signals, by their very nature, are susceptible to external interferences and noise. To ensure the purity and reliability of the data, the raw EMG signals underwent a bandpass filtering process. The chosen frequency range of 20Hz to 450Hz is a standard in biomechanical studies, effectively eliminating high-frequency noise and low-frequency drifts, thereby focusing on the frequency components that truly represent muscle activity [57]. This step was crucial in preserving the integrity of the data, ensuring that subsequent analyses were based on genuine muscle activity.

(b) Normalization: Given the inherent variability in muscle strength and exertion levels across individuals, normalization against the MVC value was imperative. This process standardized the EMG readings from the bicep, ensuring that the data was comparable across participants, regardless of their individual muscle strength. By doing so, the study could draw more generalized conclusions, making the findings more universally applicable [58].

(c) Signal Analysis: The Root Mean Square (RMS) value of the normalized EMG signals was computed. RMS is a widely accepted metric in biomechanics, offering a measure of the signal's magnitude, which, in this context, translates to muscle activity intensity. The use of a moving mean function with a window size of 200 was not arbitrary; it was chosen to provide a balance between smoothing the data and retaining the essential characteristics of the muscle activity patterns [59].

(d) Statistical Insights: The statistical tests, including t-tests and Wilcoxon signed-rank tests, were employed. These tests were chosen based on the nature of the data distribution and were instrumental in identifying any statistically significant differences in muscle activity when participants performed tasks with and without the exoskeleton. Such statistical analyses lend credibility to the findings, ensuring that the observed effects were not mere coincidences but had scientific backing [55].

While our study provided valuable insights, it was not without limitations. Firstly, the sample size was limited to ten participants, which may not be representative of the broader population. Secondly, the study focused solely on the bicep curl movement, which, although relevant, is just one of many potential tasks an individual might perform. Additionally, the study did not account for long-term use of the exoskeleton and its potential effects on muscle adaptation or dependency. Lastly, while EMG provides valuable data on muscle activity, it does not capture the complete picture, such as joint forces or detailed kinematics.

4 Results

4.1 Statistical Analysis of Impedance Controller

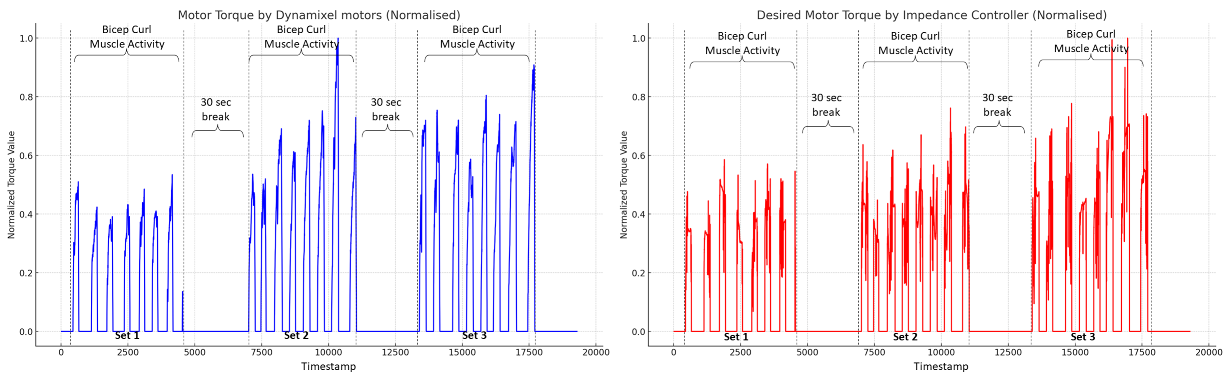


Figure 4.1: Normalised torque response of motor and desired torque respectively

Metric	Value
Pearson Correlation	0.895
Mean Absolute Error (MAE)	0.148
Root Mean Square Error (RMSE)	0.352

Table 4.1: Evaluation of impedance controller

4.1.1 Pearson Correlation (r)

The Pearson correlation coefficient between the "Motor Torque" and the "Desired Motor" is approximately 0.895. This value is close to 1, indicating a strong positive correlation. This suggests that the Dynamixel motors are generally doing a good job of following the desired torque values set by the impedance controller.

4.1.2 Mean Absolute Error (MAE)

The MAE between the "Motor Torque" and the "Desired Motor Torque" is 0.148. MAE measures the average of the absolute differences between the predicted and actual values. A smaller MAE indicates better performance. Here, the MAE is relatively low, suggesting that the motor torque generally aligns well with the desired values, with minor deviations.

4.1.3 Root Mean Square Error (RMSE)

The RMSE between the "Motor Torque" and the "Desired Motor Torque" is 0.352. RMSE gives an idea of how concentrated the data is around the line of best fit. Lower values of RMSE indicate better fit. The RMSE value here is moderate, suggesting that while there may be some outliers or occasional spikes in the error, the system generally performs well in tracking the desired torque.

4.2 Data Analysis of Questionnaire

The feedback gathered from the post-experiment survey provides a detailed understanding of how well the exoskeleton system aligns with user expectations and needs. Rated on a scale of 1 to 5, the survey results offer a nuanced perspective on various aspects of the system, from its dimensions to its comfort level.

The dimensions of the system, encompassing aspects like size, width, and length, received a favourable average rating of 4. This suggests that the design dimensions are largely in sync with user needs, allowing for a good range of motion and task efficiency. Similarly, the system's weight also received a commendable average rating of 4, indicating that the weight distribution is well-balanced, thereby minimizing user fatigue during prolonged usage.

Adjustability of the system components was a standout feature, earning a perfect average score of 5. This score emphasizes the system's adaptability, enabling users to make quick adjustments for a personalized fit. This is a crucial advantage, as it enhances user engagement and overall satisfaction.

In terms of safety, which is a paramount concern for any wearable assistive device, the system scored an uplifting average of 4. The rating in the safety category serves as a testament to the robust safety features engineered into the system, designed to mitigate risks and foster a sense of trust among users. Although there remains room for additional enhancements, this rating positively reflects the system's dependability.

The ease of use and overall comfort of the system received moderate average scores of 3. Although these scores point to areas that could benefit from further refinement, they also confirm that the system is generally straightforward to use and comfortable for short durations. These scores offer constructive insights for future design improvements, aimed at making the system even more intuitive and cozy for extended use.

The survey results are largely optimistic, underscoring the system's strong design fundamentals in areas like dimensions, weight, and adjustability. The encouraging score in the safety domain is particularly noteworthy, as it is a critical determinant for the broader acceptance of such technologies. While the scores for ease of use and comfort provide constructive feedback for future enhancements, they also affirm that the system is moving in the right direction. This user feedback will be instrumental in fine-tuning the exoskeleton system to meet both safety standards and user satisfaction more effectively.

The primary objective of this research was to critically evaluate the effectiveness of the developed elbow exoskeleton in reducing muscle strain during manual lifting tasks. The subsequent sections delve into the data presentation, statistical tests, and the inferences drawn from the results.

4.3 Hypotheses

To guide the analysis, two hypotheses were formulated:

- **Null Hypothesis** (H_o): There is no significant difference in muscle activity (quantified in terms of mean, standard deviation, and RMS value) when comparing the conditions with and without the exoskeleton.

- **Alternative Hypothesis** (H_a): A significant difference exists in muscle activity between the two conditions.

Condition	Mean (%)	Standard Deviation (%)	RMS Value (%)
With Exoskeleton	2.098	0.212	2.112
Without Exoskeleton	4.149	0.449	4.182

Table 4.2: Evaluation of User Testing with and without exoskeleton

4.4 Data Presentation

The table below provides a comprehensive overview of the muscle activity metrics under the two conditions:

4.5 Statistical Analysis of User testing

4.5.1 Processing the EMG signal

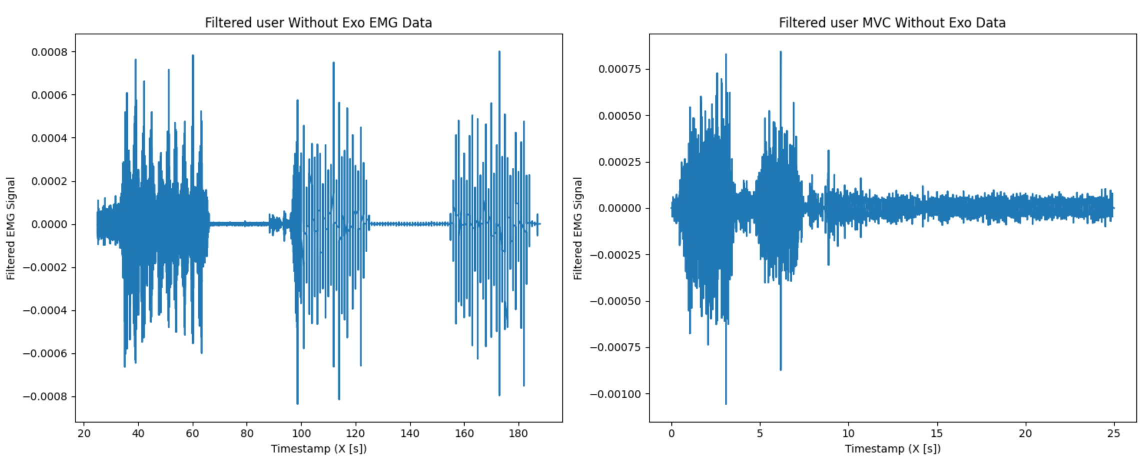


Figure 4.2: Filtered EMG signal and Filtered MVC signal respectively(Without Exoskeleton)

1. Figure:4.2 showcases filtered EMG signals of the participant, providing a cleaner representation of muscle activity by eliminating noise and artefacts. This is crucial for achieving precise and adaptable control in robotics and exoskeletons

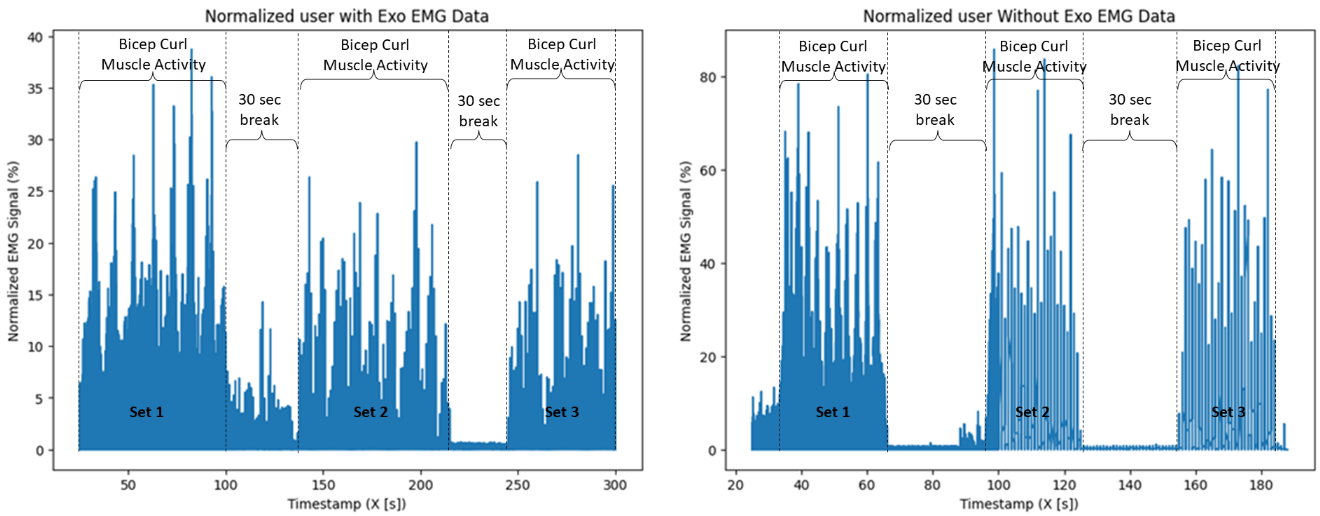


Figure 4.3: Normalised data With and without exoskeleton respectively

2. Figure:4.4 represents the normalised signal of the filtered EMG signal of the participant which are essential for comparing muscle activities across different sessions or subjects. Normalisation is particularly relevant in the context of personalised therapy in rehabilitation robots

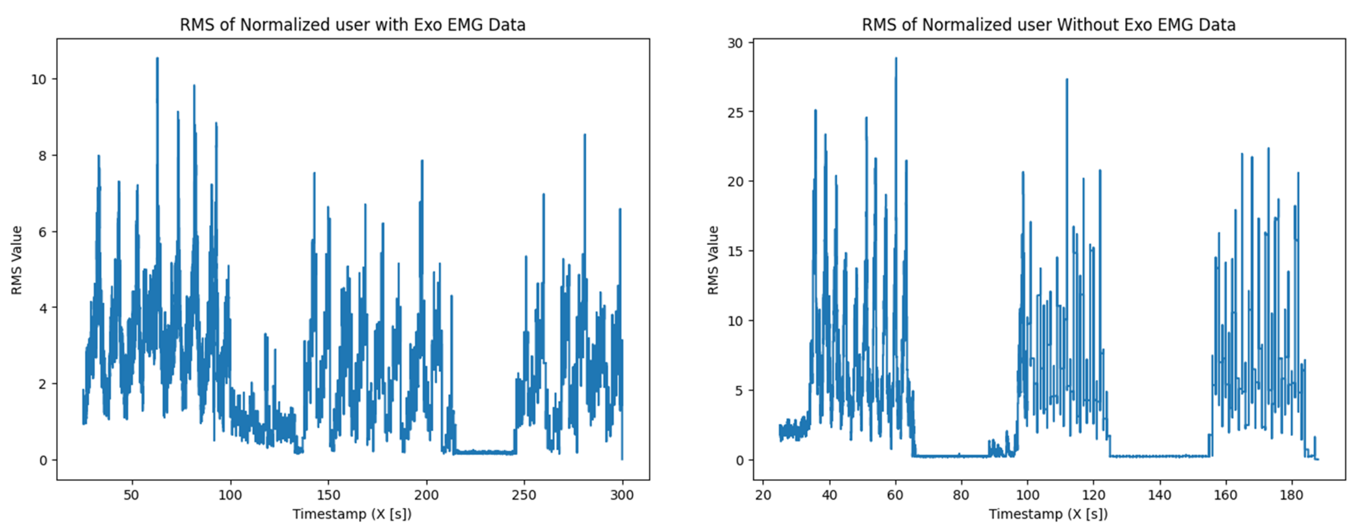


Figure 4.4: RMS signal With and without exoskeleton respectively

3. Figure:4.4 displays root mean square (RMS) EMG signals of the normalised EMG signal that offers an aggregate measure of muscle activity. RMS is particularly useful in industrial settings for assessing the effectiveness of exosuits in reducing physical strain

- **Wilcoxon Signed-Rank Test**: The Wilcoxon Signed-Rank Test was specifically selected for this study due to the non-normal distribution of the collected data. This non-parametric test is particularly useful for comparing two related samples, in our case, the muscle activity with and without the exoskeleton. The test statistic, which was found to be 0.0, is a measure of the difference between the paired observations.

  The p-value, a critical indicator in hypothesis testing, was calculated to be 0.25. In the realm of statistical analysis, a p-value greater than 0.05 typically suggests that the null hypothesis cannot be rejected. In the context of this study, the null hypothesis posited that there is no significant difference in muscle activity when the exoskeleton is worn as compared to when it is not. The obtained p-value of 0.25, being greater than the conventional alpha level of 0.05, leads us to retain the null hypothesis. This suggests that while the exoskeleton's impact on muscle activity was not statistically significant in this particular study, the observed differences could potentially be insightful for further investigation.

  It is also crucial to consider the limitations of the study, such as the small sample size and the specific conditions under which the tests were conducted. These factors could have contributed to the lack of statistical significance, indicating a need for further research with a more extensive participant pool and varied testing conditions. The Python code can be viewed in the Appendix H.

- **Shapiro-Wilk Test for Normality**:

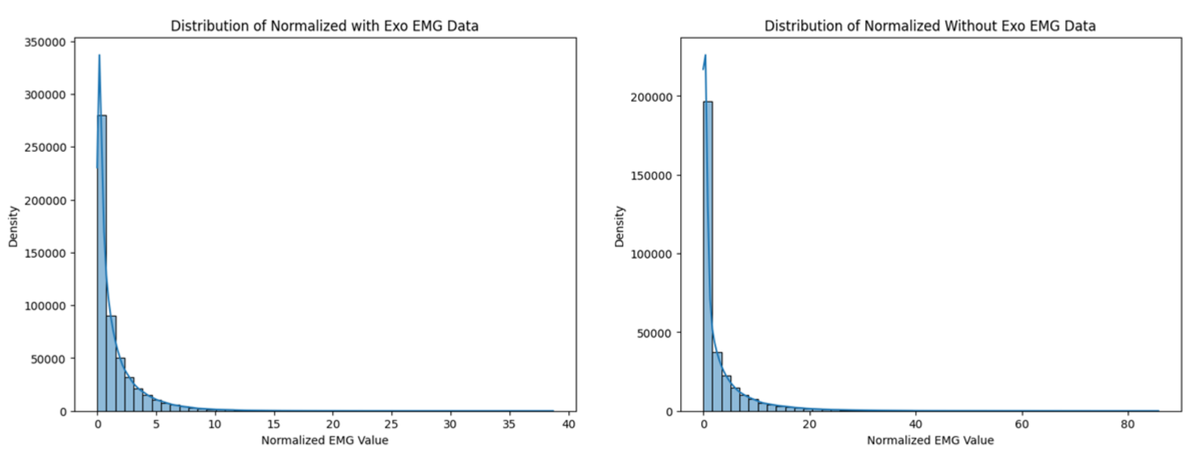


Figure 4.5: Normal Distribution of EMG signals With and without Exoskeleton

The test statistics for both conditions—0.7556 for data with the exoskeleton and 0.7565 for data without it—along with the corresponding p-values of 0.0123 and 0.0145, respectively, confirm the non-normal distribution of the data. This is a crucial observation as it informs our choice of statistical tests for further analysis.

In traditional statistical methods, the assumption of normality often underpins the validity of the results. However, in our case, the non-normal distribution led us to opt for the non-parametric Wilcoxon Signed-Rank Test. This decision aligns with the guidelines for best practices in biomechanical research, where non-parametric tests are often recommended for small sample sizes or when the data distribution deviates from normality.

The non-normal distribution of our data could also be indicative of underlying factors that might not be immediately apparent. For instance, the variability in muscle activity could be influenced by individual differences in muscle physiology, fatigue levels, or even psychological factors such as motivation or focus during the task. These nuances add layers of complexity to our research, making it all the more essential to conduct further studies with a larger and more diverse participant pool to better understand these dynamics.

By acknowledging the non-normal distribution and opting for a non-parametric test, we are adhering to rigorous scientific standards, thereby enhancing the credibility and reliability of our findings. Even though the p-value obtained from the Wilcoxon Signed-Rank Test suggests that we cannot reject the null hypothesis, this in itself is a valuable insight. It sets the stage for future research to explore why the exoskeleton did not have a statistically significant impact on muscle activity and how its design or application might be optimized for more pronounced effects. The Python code can be viewed in the Appendix H.

4.6 Analysis

The Python code can be viewed in the Appendix G.

1. **Mean Muscle Activity**: When participants were equipped with the exoskeleton, the mean muscle activity was observed to be 2.098%. This is a significant reduction when compared to the mean muscle activity of 4.149% recorded without the exoskeleton.

The nearly 50% reduction in mean muscle activity with the exoskeleton is not merely a numerical difference; it represents a substantial alleviation of muscle strain. This is particularly noteworthy because it suggests that the exoskeleton has the potential to mitigate fatigue and muscle strain during lifting tasks, thereby enhancing the user's physical capabilities.

On the other hand, the elevated mean muscle activity of 4.149% without the exoskeleton serves as a stark reminder of the increased strain that muscles undergo during manual lifting tasks. This heightened activity could potentially lead to a quicker onset of muscle fatigue, thereby increasing the risk of musculoskeletal disorders over time.

The contrast in mean muscle activity with and without the exoskeleton provides a quantitative validation of the exoskeleton's efficacy. It substantiates the claim that the exoskeleton can play a pivotal role in reducing muscle fatigue and strain, thereby contributing to safer and more efficient manual lifting tasks.

2. **Standard Deviation**: The standard deviation values offer a lens through which the consistency and reliability of the exoskeleton's performance can be scrutinized. In the case of muscle activity with the exoskeleton, the standard deviation was observed to be 0.212%. This lower value signifies a more uniform performance across varied tasks and repetitions. It suggests that the exoskeleton is effective in providing a consistent level of assistance, thereby reducing the variability in muscle activity. This consistency is crucial for the user's confidence in the device, as it implies that the exoskeleton can reliably assist in a range of manual lifting tasks without causing abrupt changes in muscle activity.

   On the other hand, the standard deviation for muscle activity without the exoskeleton was considerably higher, recorded at 0.449%. This elevated level of variability could be attributed to a multitude of factors. For instance, individual lifting techniques could vary significantly among participants, leading to inconsistent muscle activity. Additionally, the varying levels of fatigue experienced by participants during the lifting tasks could contribute to this higher standard deviation. The absence of uniform assistance, as provided by the exoskeleton, leaves room for these natural variabilities to manifest more prominently.

   The lower standard deviation when using the exoskeleton underscores its potential to offer a more reliable and consistent form of assistance, thereby possibly reducing the risk of muscle strain or injury. Conversely, the higher variability without the exoskeleton serves as a reminder of the challenges and inconsistencies that manual lifting tasks can present, emphasizing the need for assistive technologies like exoskeletons.

3. **RMS Value**: RMS values serve as a robust indicator of muscle activity. They offer a quantifiable measure of the electrical signals generated by muscle fibers during contraction, thereby providing insights into the muscle's operational state. In our study, the RMS values presented a compelling narrative about the efficacy of the exoskeleton in reducing muscle exertion.

   When participants performed tasks with the exoskeleton, the RMS value was observed to be 2.112%. This reduced value is indicative of a lower level of muscle activity, which can be interpreted as a decrease in overall muscle exertion. The implication here is significant; a lower RMS value could potentially translate to reduced muscle fatigue over extended periods of activity. This aligns with the overarching goal of our research, which is to develop an exoskeleton that can alleviate muscle strain and fatigue during manual lifting tasks.

   On the contrary, the RMS value without the exoskeleton was notably higher, clocking in at 4.182%. This elevated value signifies an increase in the magnitude of muscle activity, which could potentially lead to quicker onset of muscle fatigue and strain. The higher RMS value in the absence of the exoskeleton serves as a testament to the added strain that muscles undergo during manual lifting tasks without any assistive technology.

   The RMS values not only validate the effectiveness of the exoskeleton in reducing muscle exertion but also highlight the potential risks of manual lifting tasks when performed without assistive technology. These findings are pivotal in understanding the biomechanical advantages of integrating exoskeletons into manual labor scenarios, thereby contributing to the broader discourse on workplace ergonomics and worker well-being.

5 Discussion

The development and evaluation of an elbow exoskeleton aimed at enhancing force during manual both achievements and challenges. The literature, on exoskeletons and their potential benefits, provided a solid foundation for this research. Notably, the work of de Looze et al. [5] highlighted the potential of exoskeletons in reducing muscle strain. Similarly, the study by Huysamen et al. [6] on the biomechanical effects of wearing an exoskeleton during manual handling tasks provided valuable insights that guided our experimental design.

One of the significant achievements of this research was the successful integration of the Dynamixel MX106 motors with the Raspberry Pi 4, resulting in a seamless control mechanism. The adoption of the Impedance Control strategy, as discussed by Hogan [60], ensured that the exoskeleton was both responsive to the user's intentions and safe during interactions with external environments. The spring and damping behaviours, modelled after the principles outlined by Vitiello et al. [61], ensured a balanced behaviour of the exoskeleton.

However, while the hardware and control system showed promise, the user testing presented a mixed bag of results. The use of Electromyographic (EMG) data to assess muscle activity was inspired by the work of Burhan et al. [62], which analysed the Biceps Brachii Muscle under varying conditions. Our findings, showing a discernible reduction in mean muscle activity when participants used the exoskeleton, were encouraging. Yet, the statistical significance of these findings was not as robust as one might hope, suggesting the need for a more extensive study with a larger participant pool.

The choice of the bicep curl experiment was deliberate, given its relevance in simulating lifting tasks. The bicep curl, as highlighted by Neumann [63], is a fundamental movement that engages the bicep brachii, making it an ideal choice for our study. The observed reduction in muscle activity with the exoskeleton suggests its potential in mitigating fatigue and strain during such tasks. However, it's essential to note the limitations. The study's scope was confined to the elbow joint, and while this focus allowed for a detailed analysis, it also means that the findings might not be generalisable to exoskeletons targeting other joints or full-body systems.

Another limitation was the non-normal distribution of the data, which influenced the choice of statistical tests. While the Wilcoxon Signed-Rank Test and the Shapiro-Wilk Test for Normality were appropriate given the data's characteristics, they also come with their own set of assumptions and limitations, as discussed by Field [64].

The introduction and application of wearable exoskeletons in daily life and work environments bring forth several ethical concerns that need to be addressed:

1. **Dependence on Technology:** Over-reliance on the exoskeleton might lead to decreased muscle use, potentially causing muscle atrophy over time. While the device is designed to assist, it's essential that users don't become wholly dependent on it, which could lead to long-term health implications.

2. **Equity and Accessibility:** The availability of such advanced technology might be limited to certain economic classes or regions. This could lead to an unequal distribution of health benefits, where only those who can afford the exoskeleton can reap its advantages.

3. **Data Privacy:** With sensors collecting data, there's always a concern about where this data is stored, who has access to it, and how it might be used. Ensuring robust data protection measures is not just a technical requirement but an ethical one.

4. **Long-term Health Impacts:** The long-term effects of using an exoskeleton on joint health, bone density, and overall physical well-being are not yet fully understood. Continued research and monitoring are essential to ensure that users are not inadvertently harming their health.

5. **Workplace Implications:** In work environments, there might be a push for employees to use such devices to enhance productivity. This could lead to ethical concerns about consent, especially if workers feel compelled to use the device against their wishes.

6. **Environmental Concerns:** The production, usage, and disposal of electronic devices, including exoskeletons, have environmental implications. Ensuring sustainable production and recycling methods is an ethical imperative.

This research has added to the growing body of knowledge on exoskeletons and their potential benefits. The findings, while promising, also underscore the complexities involved in developing and evaluating such systems. Future studies might consider a more holistic approach, incorporating not just the elbow but other joints as well, to get a comprehensive understanding of exoskeletons' potential in manual lifting tasks.

5.0.1 Self-reflection

The initial stages were heavily focused on literature review and understanding the existing solutions for musculoskeletal disorders. While the theory seemed straightforward, applying it practically through the development of an elbow-supporting exoskeleton presented numerous challenges.

One of the most enlightening experiences was the realisation that even minor errors in calculations could lead to significant discrepancies in the exoskeleton's performance. This was particularly evident when calibrating the impedance controller, where a slight miscalculation could result in less-than-optimal torque output.

Our control algorithms, although theoretically sound, showed latency during real-time operations. This required not just code optimization but a comprehensive review of the algorithm's efficiency and compatibility with hardware.

The project's structure was inherently iterative, with each phase's feedback serving as a cornerstone for subsequent developments. This feedback loop, enriched by academic insights, ensured that encountered challenges metamorphosed into avenues for refinement, enhancing the project's overall efficacy.

Making sure everyone participating was safe and comfortable and the process of gathering and analysing data through IMU and EMG sensors was a steep learning curve. It taught me the importance of precision in every aspect of research.

It has not only enhanced my technical skills but also improved my ability to conduct comprehensive research. The lessons learned from this project will undoubtedly serve me well in future endeavours.

6 Conclusion

The robotics and biomechanics have witnessed significant advancements in recent years, with exoskeletons emerging as a promising solution to address various challenges in human augmentation, rehabilitation, and industrial applications. This research has the potential to enhance the force during manual lifting tasks of an elbow exoskeleton enhancing force during manual lifting tasks, with a keen focus on its implications for muscle activity and fatigue.

Our exoskeleton, designed with precision and driven by Dynamixel MX106 motors, showcased the potential of robotics in augmenting human capabilities. The integration of Raspberry Pi 4 and the implementation of an Impedance Control strategy ensured that the exoskeleton could adapt to dynamic environments, offering a seamless interaction experience for the user [60]. The control system, underpinned by the principles of Impedance Control, ensures that the exoskeleton responds adaptively to external disturbances, thereby ensuring safety and efficiency [61].

The exoskeleton has shown promising results, both in terms of its mechanical performance and its potential to alleviate muscle strain. The real-world tests, particularly the bicep curl evaluations, have been especially revealing. They've shown a significant reduction in muscle activity, confirming the device's potential to make manual tasks less strenuous. While there's still room for improvement, especially in fine-tuning the motors and the cooling system, the current outcomes are encouraging. We believe this exoskeleton could be a valuable asset in occupational settings, helping to reduce the risk of musculoskeletal disorders.

The literature review laid a robust foundation for our research, highlighting the increasing prevalence of Musculoskeletal Disorders (MSDs) in industrial settings and the potential of exoskeletons in mitigating associated risks [5]. The comprehensive analysis of 26 research papers enriched the understanding, providing insights into the current state of the art and identifying gaps that our research could address.

The user testing phase was designed, drawing inspiration from established protocols in biomechanics and ergonomics research [62]. Our choice of the bicep curl experiment was rooted in its relevance to the elbow joint and its widespread use in assessing bicep and tricep muscle activity [63]. The incorporation of EMG and IMU sensors ensured that our data collection was both comprehensive and precise. The decision to employ the Maximum Voluntary Contraction (MVC) as a normalisation factor was informed by its established efficacy in providing a standardised measure of muscle activity, allowing for more meaningful comparisons [64].

Our results, though promising, were not without limitations. The sample size, though adequate for a pilot study, could benefit from expansion in future research to ensure broader generalisability. Furthermore, while our exoskeleton was focused on the elbow joint, the human arm is a complex interplay of multiple joints and muscles. Future iterations could potentially explore a more holistic design, encompassing the wrist and shoulder joints.

This research has made significant strides in understanding the potential of exoskeletons in industrial settings. The positive implications for muscle activity and fatigue suggest that with further refinement and large-scale testing, exoskeletons could become a mainstay in industries, enhancing worker productivity while ensuring their health and safety. As we stand on the cusp of a new era in robotics and biomechanics, it is imperative to continue this line of research, exploring new frontiers and pushing the boundaries of what is possible.

7 Future Work

- **Adaptive Control Systems**: While the current impedance control approach shows potential, upcoming studies could look into control algorithms that are self-adjusting and can adapt to the unique movements and requirements of each user.
- **AI Synergy**: Utilizing machine learning algorithms could enable the exoskeleton to foresee what the user intends to do and modify its support accordingly, making the device more instinctive and easy to use.
- **Full-Body Support Systems**: Present models mainly focus on the elbow joint. Future iterations could extend to encompass the entire arm or even a full-body support system for more intricate tasks.
- **Energy Efficiency and Battery Longevity**: Power usage is a key concern for any wearable tech. Future studies might delve into creating more energy-conserving configurations or examine new sources of power.
- **Real-Time User Feedback**: The integration of tactile or other types of sensory feedback can offer users immediate data on the actions of the exoskeleton, enhancing user interaction.
- **Safety Measures**: As the technology matures, the emphasis on user safety will grow. Upcoming projects should focus on developing infallible mechanisms and protocols for emergencies.

7.1 Suggestions

- **Ethical Usage**: Like all assistive technologies, ethical use is paramount. This includes safeguarding user data if it's being collected and ensuring the device is used safely and as intended.

- **Green Manufacturing and Disposal**: The creation and end-of-life management of exoskeletons should adhere to eco-conscious principles, incorporating materials that are renewable and designs that optimize energy use.
- **Cost Management and Universal Reach**: As the adoption of this technology grows, it's crucial to maintain its financial feasibility, particularly for those who are most in need. Various economic approaches, like funding programs, partnerships with medical providers, or discounted pricing models, could be explored to achieve this.
- **User Education**: It's crucial to provide comprehensive instructions to individuals who will be utilizing the exoskeleton, ensuring they are well-equipped to handle the device safely while being aware of its constraints and maintenance procedures.
- **Inclusive Engineering**: The creation of the exoskeleton should be accommodating to a diverse user base, taking into account variations in age, physique, and physical conditions.
- **Standardization of Safety Protocols and Regulatory Monitoring**: As the adoption of this technology grows, it's essential to formulate uniform safety and performance criteria, coupled with regulatory oversight, across the sector.
- **Public Enlightenment**: Initiatives aimed at educating the general populace can demystify the advantages and drawbacks of exoskeleton usage, thus mitigating any negative perceptions and fostering a more accepting attitude.

A Appendix

User Testing Protocol

Bristol Robotics Laboratory   University of BRISTOL   UWE Bristol University of the West of England

Evaluation and development of an elbow exoskeleton for force enhancement for manual lifting

Experimental Protocol

09th August, 2023

Principal researchers: Carlos A. Cifuentes, Marcela Múnera.
Principal investigator: Adip Ranjan Das.
Participating entities: University of Bristol, University of the West of England.
Location: Bristol Robotics Lab.
This document of informed consent is arranged in two sections:

- Information about the study
- A consent form to be signed by the subject if they agree to participate in the study.

Part I: Information

These consent forms may contain words that you do not understand. Please ask the principal investigator or anyone else involved in the study to explain any information that you do not know or do not fully understand. If you wish to participate in the study, you will be given a copy of the full consent form.

Introduction

Musculoskeletal disorders (MSDs) are currently associated with the leading cause of occupational diseases in developed countries[1]. This is problematic as it is associated with high costs to employers through absenteeism, lost productivity, and increased health care, disability, and workers' compensation costs [2]. Basically, the costs caused by these diseases lead to a reduction in human capacity and directly affect the country's production [3].

Workers are exposed to different types of MSD risks including manual handling of loads (MMC), repetitive movements, and awkward postures, as well as vibration and low-temperature work, exposures related to the risk factor of MMC have an attributable fraction range in different studies from 11% to 66% for back and upper limb disorders [3]. Despite the limited number of prospective studies on the effectiveness that clearly demonstrates the benefits of using industrial exoskeletons, they are already being introduced in a wide range of industries such as construction, mining, manufacturing, warehousing, and other industries where workers perform manual material handling (MMH) tasks [4].

The use of occupational exoskeletons has reported a reduction in workers' energy burden. Companies such as Ford recorded an 83% reduction in workers' illnesses in 2015 [5]. In addition, EMG-related studies using occupational exoskeletons reported a decrease in fatigue in the workers' shoulders and biceps from 18% to 39% [5]. For this reason, the use of occupational exoskeletons requires a system that allows the validation and monitoring of the efficiency of the worker and the device, generating traceability of the information from various sensors that allows the performance of these devices.

Justification and use of results

The studies presented in this protocol may be beneficial in evaluating the performance of an industrial exoskeleton for lifting loads. This is intended to be achieved through electromyographic and kinematic analysis of the upper limb. In addition, using a qualitative assessment through perception questionnaires such as the BORG scale and the local perceived pressure scale.

Type of Research Intervention

This research will include a non-invasive measurement protocol during the preliminary study, targeting the upper limb during lifting activities.

Participant selection

A non-random sample will be used in this project on the basis of volunteers willing to participate in the project. These will be selected considering their health status and physical conditions, based on the following inclusion and exclusion criteria.

0.0.1 Inclusion criteria

- Healthy subjects
- Age between 18 and 40 years

0.0.2 Exclusion criteria

Participants will be excluded from the study if they present any of the following conditions:

- Subjects who do not achieve a score greater than 48 on the Oxford elbow score scale.
- Musculoskeletal and systemic disorders.
- Any known impairment of postural control or motor function.
- Acute pain or illness.
- Drug addiction.

1 Objective

1.1 General Objective

To evaluate the performance of an elbow exoskeleton for different work activities involving manual handling of loads.

1.2 Specific Objectives

- To analyse the changes in muscle activity and kinematics when performing the activities without and with the elbow exoskeleton.
- To assess satisfaction, usability, pain, and perception in the use of the device.

Device description

Elbow exoskeleton for force enhancement

The elbow industrial exoskeleton shown in Figure 1, is considered to be an Exosuit. It is operated by a main computer in charge of processing the information acquired from its instrumentation. The software applied for the different operating strategies of the device is implemented in the operating metasystem (ROS) which runs on Linux.

This has a hardware structure that consists of:

- Two (2) electric motors (*Dynamixel MX106T, Robotics, USA*) located in the lumbar spine that help provide the required torques to the participant in the execution of different tasks.
- Two (2) IMU sensors (*Adafruit BNO055 Absolute Orientation Sensor*) located in the wrist to control the exoskeleton.
- Two (2) straps to hold the structure on the subject's shoulders.
- One (1) 3D printed structure located on the lumbar back to allow natural movement of the back and support the two electric motors.

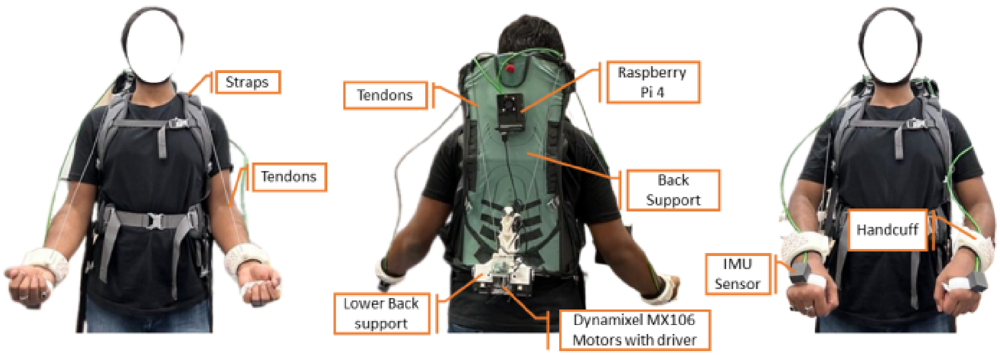


Figure 1: Elbow industrial exoskeleton

2 Methodology

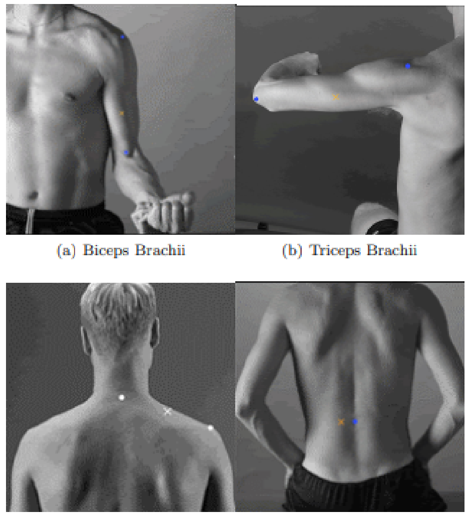
The procedure is divided into (1) Assessing the functional capacity of the elbow to verify the participant's inclusion in the study, (2) Instrumentation of electromyography (EMG) sensors, (3) the execution of the Maximum Voluntary Contraction of the 4 muscles evaluated, (4) Instrumentation with inertial sensors (IMU), and finally (5) the static/dynamic evaluation of the elbow exoskeleton. Each of the phases will be explained below:

Elbow functional capacity

For this section we will use The Oxford Elbow Score (Annexure 1) conducted by Dawson J. (2014) this consists of 12 questionnaire items with five ordinal response options each. The recall period is "During the last 4 weeks". The response to each item is scored from 0 to 4, where 0 represents greater severity. The 12 items are based on three domains (subscales): elbow pain, elbow function, and social-psychological domain. Scores for each domain are calculated as the sum of the scores for each individual item within that domain, which is then converted to a metric from 0 to 100 (a lower score represents greater severity).

Instrumentation with EMG sensors

The EMG sensors should be positioned as shown in Figure 2 according to SENIAM guidelines.



(a) Biceps Brachii (b) Triceps Brachii

(c) Upper Trapezius (d) Erector spinae

Figure 2: Group of muscles to be instrumented for measuring muscle activity in the development of the activity. The blue dots indicate the endings of each muscle and the yellow "X" indicates the place where the EMG sensors should be placed.

Maximum Voluntary Contraction (MVC)

At the beginning of the session, the maximum voluntary contraction (MVC) should be measured to normalize the intersubject measurements. For this, isometric muscle contraction exercises should be performed, where the participant executes a muscle contraction and holds it for a period of 5 seconds followed by 10 seconds of relaxation. The MVC is averaged from three consecutive measurements. The procedure necessary to find the MVC is described in detail below:

- Biceps Brachii: The participant should be seated with the elbow flexed at a right angle and the dorsal side of the forearm in a horizontal downward position. One hand is placed under the elbow to protect it from the pressure of the table and the elbow should be flexed slightly below or at a right angle, with the forearm supinated. Apply pressure against the forearm in the direction of elbow extension as shown in Fig 3.

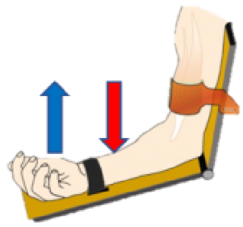


Figure 3: MVC for the Biceps Brachii muscle, the blue arrow indicates the movement direction of the person and the red arrow indicates the direction of the force to be exerted on the person.

- Triceps Brachii: The participant should be seated with the shoulder in approximately 90-degree abduction with the arm flexed 90 degrees and the palm of the hand pointing downward. The participant should extend the elbow while exerting pressure on the forearm in the direction of flexion as shown in Figure 4.

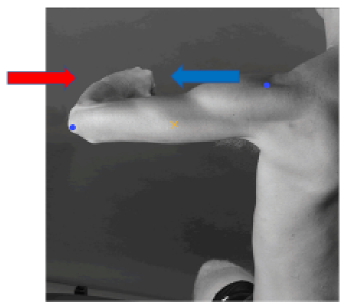


Figure 4: MVC for the Triceps Brachii muscle, the blue arrow indicates the movement direction of the person and the red arrow indicates the direction of the force to be exerted on the person.

Instrumentation with inertial sensors (IMU)

The IMU sensors should be positioned on the wrists and on the lumbar and cervical spine of the person. Before starting the session, data should be acquired with the person in an anatomical position for 3 minutes. The location of the sensors is shown in Fig 5.

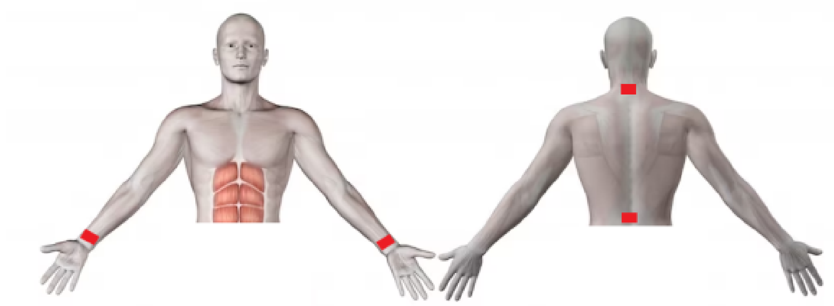


Figure 5: Inertial sensors location on the lumbar and cervical spine and on the participant's wrists illustrated in red.

The following tests are performed randomly with and without the elbow exoskeleton

Static and dynamic test

This part consists of holding a load for a certain time maintaining the same position and leaving them at three different heights on a shelf, performing only vertical movement.

1. Participant must stand facing forward, looking at a fixed point.
2. Maintain an upright posture with legs shoulder-width apart.
3. Researchers should adjust the exoskeleton to ensure it fits snugly and comfortably on the subject's arm.
4. The participant should start with arms fully extended downwards.
5. Hold a 2 kg weight with a firm grip, ensuring the palms are facing forward.
6. Slowly curl the weight up, keeping the elbow close to the torso, until the biceps are fully contracted and the weights are at shoulder level. The forearm should only be moving.
7. Hold the curled position for a moment, squeezing the biceps.
8. Slowly lower the weight back to the starting position.
9. Repeat the curl for a total of 10 repetitions.
10. Rest for 30 seconds.
11. Switch to a 2.5 kg weight.
12. Repeat steps 5-9 with the 2 kg weight.
13. Complete 3 sets for each weight, with a 1-minute rest between sets.

Addition of elbow exoskeleton

Finally, the person is instrumented with the elbow exoskeleton in order to repeat the static and dynamic test of the methodology.

Clothing Conditions

The recommended clothing for the described experimental protocol includes comfortable clothing, such as a T-shirt and sports shoes, and preferably a short-sleeved shirt. Likewise, it is recommended that the participant should tie up their hair in case it may be affected by the instrumentation equipment used.

Risks

By participating in this research you expose yourself to no greater risk than if you did not.

Discomfort

While participating in this research it is possible that the participant may experience some physical discomfort in the instrumentation with the electromyography sensors and inertial sensors. However, in case of pain, fatigue or any injury to the skin, the test will be completely suspended.

Benefits

Participating in the conduct of this study will have no known benefit for your health, but will contribute to the fulfilment of the research purpose. There may be no benefit to the population of interest at this stage of the research.

Incentives

You will not be given any money, gifts or incentives for taking part in this research.

Confidentiality

Within the framework of this study, certain information concerning the subject of study will be collected for research purposes. However, this information will be recorded anonymously, in this case, it can be linked to the person to whom it relates except by a code or other means known only to the owner of the information. In this way, the personal information of the participating subjects is protected. Their identity will never be revealed or published.

Sharing the Results

During the study, participants will be able to know at all times the status of the research project and the preliminary results. Dissemination of the final results obtained from this research will be sought so that other interested persons can learn. Confidential information will not be shared.

Right to Refuse or Withdraw

You do not have to take part in this research if you do not want to. You may stop participating in the research at any time during the study if you feel it is appropriate. It is your choice and your right to refuse to participate or to withdraw at any time which will be respected.

B Appendix

Participant Information Sheet

Participant Information Sheet

OCCUPATIONAL UPPER-LIMB EXOSKELETON FOR ELBOW JOINT

Introduction
You are invited to participate in student research being conducted at the University of the West of England, Bristol (UWE). Before you decide to participate, it's crucial to understand the research's purpose and what participation entails. Please read the following information carefully. For any questions or additional information, contact [Adip Ranjan Das], [MSc. Robotics], UWE, Bristol [Adip2.Das@live.uwe.ac.uk].

Who is organizing this research?
The student researcher is [Adip Ranjan Das], supervised by [Dr. Carlos Cifuentes]. You can find the supervisor's profile at [https://people.uwe.ac.uk/Person/CarlosCifuentes].

What is the purpose of this study?
The primary objective of this research is to evaluate the effectiveness and comfort of an occupational elbow upper limb exoskeleton designed for industrial workers. Through various experiments, we aim to understand its impact on reducing muscle activation and ensuring safety during repetitive or strenuous tasks.

Why have I been invited to take part?
We are keen to understand how the exoskeleton performs in real-world industrial settings and if it provides tangible benefits to healthy people. Your feedback and experience will be invaluable in refining the design and functionality of the exoskeleton.

Do I have to take part?
Participation is entirely voluntary. If you choose to participate, you'll receive this information sheet and a consent form to review. You can withdraw without providing a reason up to seven working days after participation. If you decide to withdraw, your data will be destroyed and excluded from the study results. Withdraw by emailing Adip Ranjan Das (Adip2.Das@live.uwe.ac.uk) or Dr Carlos Cifuentes (carlos.cifuentes@uwe.ac.uk).

What will happen to me if I take part and what do I have to do?
Upon agreeing to participate, you'll be introduced to the occupational elbow upper limb exoskeleton. After a brief tutorial, you'll be asked to perform a bicep curl that mimic typical industrial activities, wearing the exoskeleton.

- You will be instructed on the proper use of the exoskeleton, which will take around 15 minutes.
- For safety, a body lifting device will be in place.
- You'll wear inertial sensors and EMG sensors on your arm, secured by a belt in your biceps, tricep and forearm muscles and IMU sensor in your wrist.
- The session will involve activities such as:
  1. Standing still for 30 seconds.
  2. Performing bicep curls with weights of 2.5kg for 10 times.
  3. The activity will be repeated 3 times with 30 sec break.
  4. The entire session will last approximately 30-40 minutes.

What are the benefits of taking part?
While there are no immediate personal benefits, your contribution will help refine a tool designed to enhance worker safety and efficiency in industrial settings.

What is the possible risk of taking part?
No significant risks are anticipated. If you feel discomfort at any point, you can request to stop the activity. The supervisor (Dr Carlos Cifuentes) has extensive experience conducting and supervising such research and will assist the student in conducting it sensitively. These factors were considered when designing the study.

What will happen to your information?
All the information that you give will be kept confidential and anonymized at UWE Bristol. Hard copy research material will be kept in a secure setting and digital data will be stored on the University's secure OneDrive system which only the student and supervisor will have access in accordance with the Data Protection Act 2018 and General Data Protection Regulation requirements. Your anonymized data will be analyzed together with other interview and file data, and we will ensure that there is no possibility of identification or re-identification from this point."

Where will the results of the research study be published?
The findings of this research may be used to write my master's dissertation, as well as in publications in academic journals, for teaching purposes, and in the open-access Research Repository at the University of the West of England. Your name or any other identifier will not appear in any of these publications, and your data will be collected and used anonymously. All information gathered will be anonymized and confidential, and participants will never be identified. The University will process all information gathered during this research project in accordance with the terms.

All the data will be stored under an identifier until the end of the withdrawal period.
If you have any complaints, comments or concerns about this research or how the study is executed, please contact Adip Ranjan Das (Adip2.Das@live.uwe.ac.uk) or Dr Carlos Cifuentes (carlos.cifuentes@uwe.ac.uk).

Who has ethically approved this research?
The project has been reviewed and approved by the University of the West of England University Research Ethics Committee.

What if something goes wrong?
If you have any concerns, queries and/or complaints please contact Dr Carlos Cifuentes (carlos.cifuentes@uwe.ac.uk) in the first instance.

What if I have more questions or do not understand something?
If you have any questions regarding this research, please contact Adip Ranjan Das (Adip2.Das@live.uwe.ac.uk) or Dr Carlos Cifuentes (carlos.cifuentes@uwe.ac.uk).

You will be given a copy of this Participant Information Sheet and your signed Consent Form to keep.

Thank you for agreeing to participate in this research.

C Appendix

Participant Consent Sheet

University of BRISTOL

UWE Bristol University of the West of England

Consent Form

Study Title: *User study for the occupational upper-limb exoskeleton for the elbow joint*

This consent form will have been given to you with the Participant Information Sheet. Please ensure that you have read and understood the information contained in the Participant Information Sheet and asked any questions before you sign this form. If you have any questions please contact a member of the research team, whose details are set out on the Participant Information Sheet.

If you are happy to take part in this study please sign and date the form. You will be given a copy to keep for your records.

Please read the statements below and sign below to give consent:

I have read and understood the information sheet
I have been given the opportunity to ask questions and have had my questions answered to my satisfaction.
I am aware of the risks and benefits of taking part in the study
I am aware that data collected will be anonymised, kept in accordance with General Data Protection Regulation (GDPR), and will be viewed and analysed by the research team as part of their studies.
I am aware that I have the right to withdraw consent and discontinue participation without penalty before or during the study.
I am aware that I have the right to withdraw my data from the experiment up to 7 days after the completion of the experiment, using the participant ID that the researcher will provide.
I have freely volunteered and am willing to participate in this study.
I am willing to have my questionnaire responses collected.
I consent to physical contact for the purpose of placing sensors.
I am aware that the experimenter may come into close contact with me, regardless of gender, during the study.

Name (Printed)……………………………………………………………………………

Signature………………………………………………………… Date……………………..

D Appendix

Pre-Experiment Questionnaire

Age:	________________
Gender:	1. Male 2. Female 3. Non-Binary 4. Prefer not to say
Educational Level:	1. Primary 2. Secondary 3. Higher education 4. Undergraduate 5. Masters 6. PhD
Frequency of exercise (hours per week):	________________
Do you have any Musculoskeletal issues in the left upper limb?	1. Yes 2. No
Do you have pain in your left elbow?	1. Yes 2. No
Which is your dominant side?	1. Left 2. Right

E Appendix

Post-Experiment Questionnaire

This satisfaction survey consists of 6 questions. Please mark your level of satisfaction using the following scale from 1 to 5:

1. Not satisfied
2. Not very satisfied
3. More or less satisfied
4. Satisfied
5. Very satisfied

For each question in which you state that you are not satisfied, please write in the Comments section the reason.

Question	**1**	**2**	**3**	**4**	**5**
The dimensions (size, width, length) of the system?					
The weight of the system?					
The ease of adjusting system parts?					
Safety and the possibility of not suffering any damage from the system?					
Ease of use of the system?					
System comfort?					

Table E.1: Post study questionnaire

F Appendix

Demographic data for the user study

Table F.1: Demographic Data of Participants

Characteristic	**Number of Participants**
Total Participants	10
Health Status	All Healthy
Age 20-30	8
Age 31-40	2
Left Dominant Hand	1
Right Dominant Hand	9
Male	7
Female	3

G Appendix

EMG Data Analysis python code

```
#!/usr/bin/env python

import pandas as pd
import matplotlib.pyplot as plt
from scipy.signal import butter, filtfilt
import numpy as np
import seaborn as sns

# Load the CSV files
# with Exoskeleton
exo_emg_df = pd.read_csv('UserTesting/user1/user1ExoEMG.csv')
mvc_exo_df = pd.read_csv('UserTesting/user1/user1MVCExo.csv')

# without Exoskeleton
# exo_emg_df = pd.read_csv('UserTesting/user1/user1WExoEMG.csv')
# mvc_exo_df = pd.read_csv('UserTesting/user1/user1MVCWExo.csv')

# Plotting for the first CSV file
plt.figure(figsize=(15, 6))

plt.subplot(1, 2, 1)
plt.plot(exo_emg_df['X [s]'], exo_emg_df['Trigno sensor 1: EMG 1 [Volts]'])
plt.title('user with exo EMG Data')
```

```python
plt.xlabel('Timestamp (X [s])')
plt.ylabel('Trigno sensor 1: EMG 1 [Volts]')

# Plotting for the second CSV file
plt.subplot(1, 2, 2)
plt.plot(mvc_exo_df['X [s]'], mvc_exo_df['Trigno sensor 1: EMG 1 [
    Volts]'])
plt.title('user MVC Exo Data')
plt.xlabel('Timestamp (X [s])')
plt.ylabel('Trigno sensor 1: EMG 1 [Volts]')

plt.tight_layout()
plt.show()

# Bandpass filter design parameters
lowcut = 20  # lower cutoff frequency
highcut = 450  # upper cutoff frequency
fs = 1000  # sampling frequency
order = 4  # filter order

# Designing the bandpass filter
b, a = butter(order, [lowcut, highcut], btype='band', fs=fs)

# Applying the filter to the EMG signals from both CSV files
exo_emg_filtered = filtfilt(b, a, exo_emg_df['Trigno sensor 1: EMG 1
    [Volts]'])
mvc_exo_filtered = filtfilt(b, a, mvc_exo_df['Trigno sensor 1: EMG 1
    [Volts]'])

# Plotting the filtered signals
plt.figure(figsize=(15, 6))

```

```
plt.subplot(1, 2, 1)
plt.plot(exo_emg_df['X [s]'], exo_emg_filtered)
plt.title('Filtered user with Exo EMG Data')
plt.xlabel('Timestamp (X [s])')
plt.ylabel('Filtered EMG Signal')

plt.subplot(1, 2, 2)
plt.plot(mvc_exo_df['X [s]'], mvc_exo_filtered)
plt.title('Filtered user MVC Exo Data')
plt.xlabel('Timestamp (X [s])')
plt.ylabel('Filtered EMG Signal')

plt.tight_layout()

# Compute the absolute value of the filtered signals
exo_emg_abs = abs(exo_emg_filtered)
mvc_exo_abs = abs(mvc_exo_filtered)

# Plotting the absolute values of the filtered signals
plt.figure(figsize=(15, 6))

plt.subplot(1, 2, 1)
plt.plot(exo_emg_df['X [s]'], exo_emg_abs)
plt.title('Absolute Filtered user with Exo EMG Data')
plt.xlabel('Timestamp (X [s])')
plt.ylabel('Absolute EMG Signal')

plt.subplot(1, 2, 2)
plt.plot(mvc_exo_df['X [s]'], mvc_exo_abs)
plt.title('Absolute Filtered user1MVCExo Data')
plt.xlabel('Timestamp (X [s])')
plt.ylabel('Absolute EMG Signal')
```

```
plt.tight_layout()
plt.show()

# Find the three maximum values in the absolute filtered signal from
    user1MVCExo.csv
top_3_values = sorted(mvc_exo_abs, reverse=True)[:3]

# Calculate the average of these three maximum values
mvc = sum(top_3_values) / 3

# Normalize the absolute filtered signal from user Exo EMG.csv using
    the calculated mvc
normalized_exo_emg = (exo_emg_abs / mvc) * 100

# Plotting the normalized signal
plt.figure(figsize=(8, 6))
plt.plot(exo_emg_df['X [s]'], normalized_exo_emg)
plt.title('Normalized user with Exo EMG Data')
plt.xlabel('Timestamp (X [s])')
plt.ylabel('Normalized EMG Signal (%)')
plt.show()

# Define a function to compute the RMS value using a moving mean
def moving_rms(signal, window_size):
    squared_signal = signal ** 2
    moving_avg = np.convolve(squared_signal, np.ones(window_size)/
    window_size, mode='valid')
    return np.sqrt(moving_avg)

# Compute the RMS value for the normalized exo_emg signal
window_size = 200
```

```
rms_signal = moving_rms(normalized_exo_emg, window_size)

# Plot the RMS signal for visualization
plt.figure(figsize=(8, 6))
plt.plot(exo_emg_df['X [s]'][window_size-1:], rms_signal)
plt.title('RMS of Normalized user with Exo EMG Data')
plt.xlabel('Timestamp (X [s])')
plt.ylabel('RMS Value')
plt.show()


# Define a function to compute the values for each window
def compute_windowed_values(signal, window_size):
    num_windows = len(signal) - window_size + 1
    means = np.zeros(num_windows)
    std_devs = np.zeros(num_windows)
    rms_vals = np.zeros(num_windows)

    for i in range(num_windows):
        window = signal[i:i+window_size]
        means[i] = np.mean(window)
        std_devs[i] = np.std(window)
        rms_vals[i] = np.sqrt(np.mean(window**2))

    return means, std_devs, rms_vals

# Compute the windowed values for the RMS signal
means, std_devs, rms_vals = compute_windowed_values(rms_signal,
    window_size)

# Create a DataFrame to store the values
df_result = pd.DataFrame({
```

```
    'Mean': means,
    'Standard Deviation': std_devs,
    'RMS Value': rms_vals
})

# Calculate the mean of all columns in the df_result DataFrame and
    print
mean_values_result = df_result.mean()

# Plotting the distribution of normalized user Exo EMG data
plt.figure(figsize=(8, 6))
sns.histplot(normalized_exo_emg, kde=True, bins=50)
plt.title('Distribution of Normalized with Exo EMG Data')
plt.xlabel('Normalized EMG Value')
plt.ylabel('Density')
plt.show()
```

H Appendix

Statistical Analysis python code

```
#!/usr/bin/env python

from scipy.stats import wilcoxon, shapiro
import seaborn as sns
import matplotlib.pyplot as plt
lues with the exoskeleton
means_with_exo = [2.098212, 0.212272, 2.112335] # mean, standard deviation, rms value

# Values without the exoskeleton
means_without_exo = [4.149042, 0.449486, 4.181619] # mean, standard deviation, rms value

# Compute Wilcoxon signed-rank test
w_stat, p_value_wilcoxon = wilcoxon(means_with_exo, means_without_exo)

# Check for normal distribution using Shapiro-Wilk test
shapiro_with_exo = shapiro(means_with_exo)
shapiro_without_exo = shapiro(means_without_exo)

print(w_stat, p_value_wilcoxon, shapiro_with_exo, shapiro_without_exo)
```

I Appendix

Gantt Chart

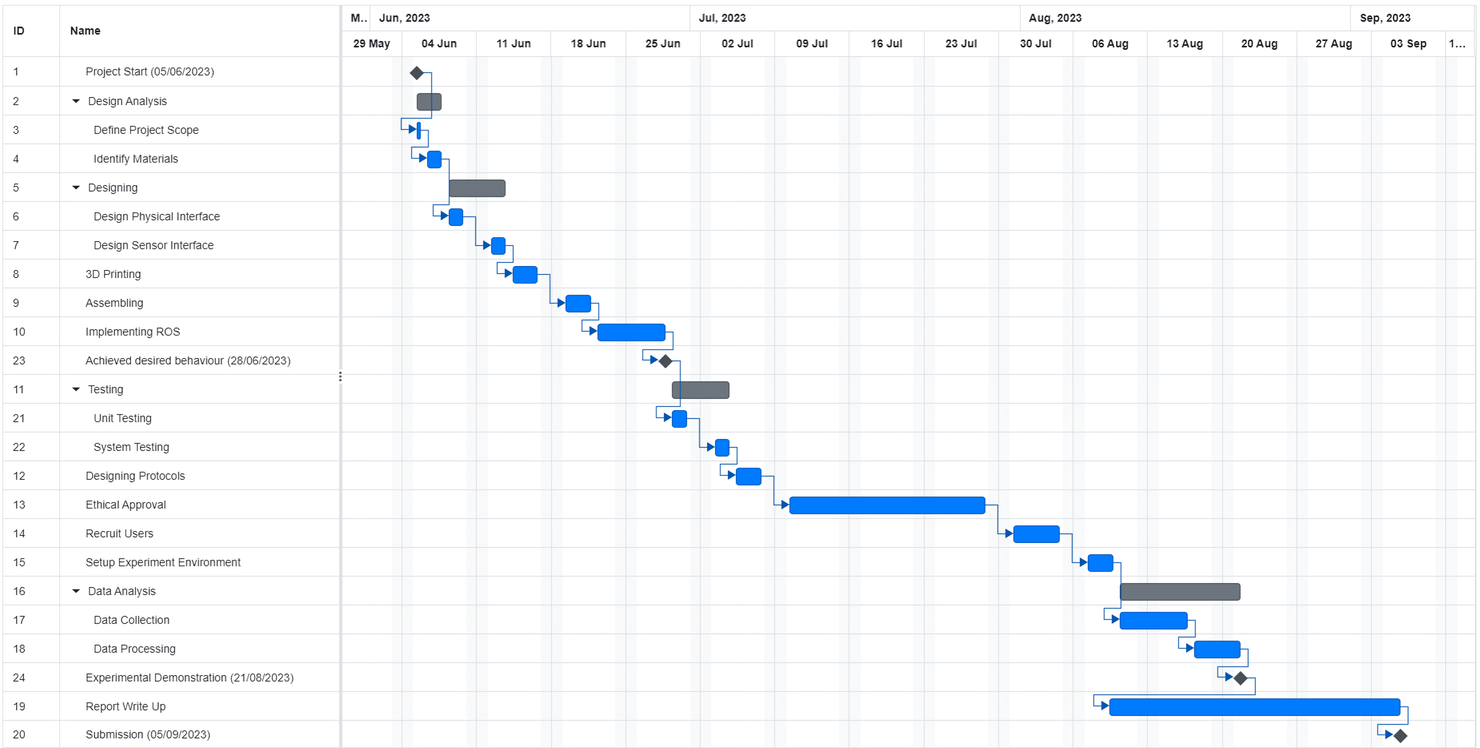


Figure I.1: Gantt Chart for the Development of an Occupational Upper-Limb Exoskeleton Project (June 5, 2023 - September 5, 2023)

J Appendix

Risk Assessment

Table J.1: Hazard Identification and Control Measures

Hazards Identified	Existing Control Measures	S	L	Risk Level	Additional Control Measures	S	L	Risk Level
Excessive force exerted by the motor leads to potential injury.	The force exerted by the motor is limited by controlling the current.	3	2	6	Regularly calibrate and test the motor's force limits.	3	1	3
Motor pulling with excessive force, risking dislocation or severe injury.	Limitation for the motors in software to prevent over-pulling.	4	2	8	Implement real-time force feedback systems to monitor and adjust the force.	4	1	4

Continued on next page

Table J.1 – continued from previous page

Hazards Identified	Existing Control Measures	S	L	Risk Level	Additional Control Measures	S	L	Risk Level
Loose connections lead to malfunction or injury.	Ensure all connections are secured.	3	2	6	Use lockable connectors and regular training for operators on connection checks.	3	1	3
Exposed wires lead to electric shocks.	All wires are insulated	3	2	6	Implement a routine electrical safety inspection.	3	1	3
Injury due to malfunction or unexpected behaviour of the exoskeleton.	Selection of healthy individuals for trials and regular system checks.	3	2	6	Provide training to users on the safe operation and what to expect.	3	1	3

Continued on next page

Table J.1 – continued from previous page

Hazards Identified	Existing Control Measures	S	L	Risk Level	Additional Control Measures	S	L	Risk Level
The system doesn't stop in case of emergency or malfunction.	Emergency stop button installed to cut power supply immediately.	5	2	10	Regular testing of the emergency stop button and backup power-off mechanisms.	5	1	5

K Appendix

Table K.1: Different exoskeletons developed for lifting task

Exoskeleton name	Exoskeleton /Exosuit	DOF	Active /Passive	Assistive Joints	Torque	Applications
Exo4Work	Exoskeleton	6	Passive	Shoulder	9 Nm	Lifting task, overhead works
Exo-Jacket 2.0	Exoskeleton	9	2 Active, 7 Passive	1 Shoulder (active), 1 Elbow (active)	40 Nm	Lifting heavy objects, carrying heavy objects
Lightweight Active Upper Extremity Exoskeleton	Exosuit	1	Active	Elbow (active)	16 Nm	Lifting heavy objects
Cable-Driven Soft Exosuit	Exosuit	9	Active	1 Elbow (active), 8 Fingers	45 Nm	Support heavy loads
Soft Exosuit for Assistance of the Elbow Comprises	Exosuit	NA	Active	1 Elbow	6 Nm	Lifting heavy loads

Table K.1 continued from previous page

Exoskeleton name	**Exoskeleton /Exosuit**	**DOF**	**Active /Passive**	**Assistive Joints**	**Torque**	**Applications**
Upper Limb Hybrid Exoskeleton	Exoskeleton	2	1 Passive, 1 Active	Elbow (active), Shoulder (passive)	Passive: Gravity compensation (shoulder), Active: Elbow 50 Nm	Overhead industrial tasks, elevation tasks
Soft Elbow Exosuit	Exosuit	1	Active	1 Elbow	30 Nm	Lifting task
Hybrid Bimanual Exoskeleton (Modified COMAU Exoskeleton)	Exoskeleton	2	Hybrid	1 Elbow (active), 1 Shoulder (passive)	26 Nm	Lifting task
Bidirectional Elbow Exoskeleton	Exoskeleton	1	Active	1 Elbow	3.822 Nm	Lifting heavy objects
Semi-Active Assistive Exoskeleton (Elbow Joint)	Exoskeleton	1	Hybrid	1 Elbow	50 N (simulated loads)	Lifting heavy objects
LUXBIT	Exosuit	1	Active	Elbow	24.5 Nm	Flexion extension movement

Table K.1 continued from previous page

Exoskeleton name	Exoskeleton /Exosuit	DOF	Active /Passive	Assistive Joints	Torque	Applications
Non-Humanoid Structure Mode	Exoskeleton	3	Active	1 Elbow (active), 2 Shoulder (active)	245 Nm	Lifting heavy loads
Parallel-Structured Upper Limb Exoskeleton	Exoskeleton	7	Active	Elbow/Shoulder	NA	Lifting heavy loads

L Appendix

Total budget for the development of exoskeleton

Item	**Units**	**Item price**	**Total**
Raspberry Pi 4 Model B	1	£55	£55
DYNAMIXEL MX-106T	2	£597.90	£1195.80
BNO055 (Adafruit 9-DOF IMU)	2	£39.18	£78.36
12V 8A Power Supply DC	1	£16.90	£16.91
Back Pack	1	£150	£150
Steel wire cable	2	£7	£14
Total			£1510.07

Table L.1: Total budget to develop the upper limb cable-driven exoskeleton

M Appendix

Ethical Review

MSc project experiment permission form for EMATM0055

Lead supervisor name: Dr. Carlos Cifuentes

Student name(s): Adip Ranjan Das

Student ID(s): 22071780

Project title: Development of Occupational Upper-Limb Exoskeleton

Summary of the proposed experiment(s):

This project is the mechatronic design of an elbow exoskeleton to empower workers to lift objects; it involves the characterization and control of the system, the design of the physical and sensor interfaces and user testing

For projects to fall within the scope of this ethics process, all answers to the following questions must be "No". If ANY questions are answered with a "Yes", a full ethics application must be submitted and approved before undertaking experimental work. For a fuller description of what is/isn't covered by this process, please check the "Blanket ethics approval process document" (available on the Unit Blackboard page).

Does the proposed experiment gather data from animals? Yes/No (No)

Does the proposed experiment gather data from a vulnerable population? Yes/No (No)

Does the proposed experiment gather sensitive information? Yes/No (Yes)

Does the proposed experiment take photos or videos of people? Yes/No (No)

Does the proposed experiment gather other data which, if lost, would allow participants to be identified? Yes/No (No)

Does the proposed experiment gather data from people who have not given full informed consent? Yes/No (No)

Does the proposed experiment trick or deceive participants in any way? Yes/No (No)

Does the risk assessment for the proposed experiment indicate a greater than low risk of physical or mental harm? Yes/No (No)

Does the proposed experiment gather data from more than 100 participants? Yes/No (No)

Will participants be recruited via methods other than word of mouth, posters, email lists (if permitted) and online forums (where explicitly allowed by the forum administrators)? Yes/No (No)

I certify that the above information is accurate and that I have read the relevant section of the project handbook.

Date: 11/08/2023 **Student signature(s):**

I certify that I have discussed the methodology of the proposed experiment with the student(s) in detail and that I am satisfied the above information is accurate.

Date: 11/08/2023 **Lead supervisor signature(s):**

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