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Exoskeleton Robot for Upper Limb Rehabilitation: Design Analysis and Control

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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Mechatronics Engineering at The University of Auckland.
Abstract

Current physical rehabilitation services for stroke utilize a manual hands-on approach with little to no application of modern technology. As a result, physiotherapy treatment is lacking in availability, is highly subjective and can only employ very basic exercises. Increasing efforts are being made in the research and development of rehabilitation robots to address these issues.

This research explores the use of an exoskeleton robot for physical rehabilitation of the human upper limb. Analysis of past exoskeleton designs have revealed major limitations in these exoskeletons’ shoulder mechanism which limit the range of motion and the movements that can be performed on the shoulder. To overcome the shortcomings of past mechanism designs, a novel 4R mechanism is proposed. However, there are a range of kinematic designs of the 4R mechanism that can meet the performance requirements of a shoulder exoskeleton. To address this, a set of performance criteria are formulated and the NSGA II optimization algorithm is applied to identify an optimal design. The resulting 4R mechanism is capable of reaching the entire shoulder workspace with high performance and without mechanical interference. Performance comparisons with other shoulder mechanism designs confirm the optimized 4R mechanism has superior performance.

The optimized 4R mechanism is then used to develop a 5 DOF active exoskeleton system for the shoulder and elbow joints. To maneuver the exoskeleton, an algorithm is developed to generate smooth point-to-point trajectories that are similar to the trajectories in normal human motion. This algorithm is further expanded into a trajectory planner which combines a sequence of point-to-point movements into a single smooth trajectory. To control the exoskeleton, two types of interactive control strategies are developed. Admittance control allows the user’s limb to move the exoskeleton by applying forces at the designated interfaces, during which the exoskeleton can assist or resist user movement. Impedance control involves actuation of the exoskeleton to move the user's limb through a specified trajectory with an artificial compliance. Experimental results on a healthy human subject demonstrate the diverse capabilities of the exoskeleton. The tools developed in this research open up new possibilities in the field of physical rehabilitation.
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Robots are used to perform tasks that are hazardous, tedious or impractical for a human being to undertake. They have been applied successfully in many fields such as in manufacturing where robots provide high speed and reliable product fabrication and in space exploration where the robot operates in a highly dangerous environment. A relatively new application of robotic technology is in the area of healthcare where the increasing elderly population has motivated the development of new tools for people with physical disabilities. However, development of healthcare robots involves new challenges in design and control since they will be interacting directly with the human user. This research aims to develop an exoskeleton robot for upper limb rehabilitation with a focus on the highly complex human shoulder joint. This chapter discusses the limitations of conventional rehabilitation services and the issues in developing an upper limb rehabilitation robot. The research objectives are described and an outline of this thesis is presented.

1.1 Physical Rehabilitation

The goal of physical rehabilitation is primarily to recuperate a patient from impairment or disability and improve mobility, functional ability and quality of life. This impairment can be the result of a stroke, injury or a neurological disease. The most common cause of adult
disability in developed countries is stroke [1]. Stroke is caused by either a disruption of blood supply to the brain or the rupturing of a blood vessel and results in damage to the brain. In New Zealand, an estimated 6,000 stroke cases occur every year with approximately two thirds of the victims surviving the stroke. The Stroke Foundation of New Zealand estimates that the number of stroke patients in New Zealand has reached 45,000 in 2011 [2]. As the population of the baby boom generation continues to age and life expectancy continues to improve, the number of elderly in the population is expected to increase in the next few decades [3]. As a result, stroke cases can be expected to increase as well.

Survivors of stroke commonly experience hemiplegia, the paralysis or loss of physical strength on one side of the body. Impairment of the upper limb can cause difficulties in performing basic day-to-day activities such as eating, dressing and hygiene tasks which can have a huge impact on the patient’s life. Patients with severe disabilities may be unable to perform vital tasks such as drinking from a cup or bottle and will require regular assistance from other people. Physical therapy (or physiotherapy) is the main treatment for these disabilities, a process that allows the stroke patient to relearn the best possible use of their limbs and regain independence. Current rehabilitation services utilize manual hands-on treatment provided by a physiotherapist. However, rehabilitation therapy can continue throughout most of a stroke patients’ life [4] and is therefore labor intensive and costly. As a result, current rehabilitation services are often unable to provide sufficient and timely treatment which hinders the rate of patient recovery.

There are a number of factors that have been found to contribute to faster motor recovery, many of which have not been taken full advantage of due to the limitations in current rehabilitation services [1]. It has been known that therapy is most effective if performed early after stroke [5], but this is not always available. In addition, studies have found that intensive therapy and task-based exercises contribute significantly to motor recovery [4]. Physiotherapy for stroke survivors after completing acute stroke rehabilitation showed continued improvement, suggesting that recovery can continue for many years after stroke. As the population of stroke patients continues to grow, providing adequate rehabilitation treatment to patients can be expected to become increasingly difficult due to the limitations of current rehabilitation services.

These issues are the impetus of recent research on robots for physical rehabilitation. Rehabilitation robots have the potential to overcome the limitations of conventional rehabilitation methods and can enable the development of new types of rehabilitation treatment. Compared to manual therapy, rehabilitation robots have the potential to provide
intensive rehabilitation consistently for a longer duration [6] and is not affected by the skills and fatigue level of the therapist. Robots can treat patients without the presence of the therapist, enabling more frequent treatment and potentially reducing costs in the long term. In addition, it is possible for a rehabilitation robot to accurately measure quantitative data to evaluate the patient’s condition. The use of specially designed virtual games with the robot can provide a more entertaining therapy experience, promoting the patient to put in their own effort into the exercises [7].

Although a robot can provide many benefits, there are some processes in physiotherapy that may be difficult to achieve with a robot. For example, palpation is an important part of physiotherapy which involves the use of hands to examine the body. To achieve this with a robot, it may be necessary to cover the limb with actuators and sensors which is challenging and costly with current technology. The current goal in developing rehabilitation robots is to address some of the key issues that are limiting physiotherapy and enhance existing physiotherapy by providing physiotherapists with tools that utilize state-of-the-art technologies.

Current rehabilitation services in practice have the following limitations:

1. Travelling difficulty: Patients are required to relocate to rehabilitation clinics or medical centers to receive treatment. This is inconvenient, time-consuming and can be very challenging for an individual with physical disabilities. Rehabilitation robots can allow patients to receive treatment in more convenient locations such as at home or at work.

2. Limited availability: Rehabilitation exercises involve manual hands-on treatment with the physiotherapist. This is tiring for both the patient and the physiotherapist and is difficult to perform continuously for extended periods of time. Therefore frequent treatment is preferable over long rehabilitation sessions. However this is difficult to achieve due to the travelling difficulties and the limited availability of physiotherapists. Physiotherapists can only attend to a limited number of patients due to their physical involvement in rehabilitation sessions. Rehabilitation robots can be used at any time and can operate for an indefinite period of time.

3. Subjectivity: Physiotherapists evaluate patient disability and recovery based on their own opinion. This can be inaccurate and lead to treatment that may not be optimal for the patient’s condition. Furthermore, evaluations are inconsistent between different physiotherapists which makes it difficult to compare outcome results and reduces confidence in physiotherapy research. A rehabilitation robot can be designed to
provide an accurate objective measurement of a patient’s disability characteristics at specific joints and muscle groups in the body.

4. Lack of patient motivation: Patients recover faster when they put effort into their rehabilitation exercises [7]. Conventional rehabilitation methods tend to involve movements that are repetitive, uninteresting and tedious. Since the patient is not enjoying the exercise, this will likely cause a reduction in the amount of voluntary effort put in by the patient. The recovery process can be slow so patience and perseverance will be required from the patient during the rehabilitation period. On the other hand, rehabilitation robots can be used in conjunction with virtual games to provide the patient with fun and rewarding exercises which can motivate the patient to put in extra effort.

5. Limited complexity of rehabilitation treatment: Physiotherapists are limited to providing rather basic treatment with currently available tools. It is difficult to provide a suitable amount of assistance only when required and to accurately manipulate multiple joints simultaneously without a complex multi-joint system. A rehabilitation robot can provide assistance only when needed and can be designed to move each joint independently to generate complex movements that resemble functional tasks.

1.2 Robots for Rehabilitation

Early rehabilitation robots made use of the better understood industrial robots as a starting point for development [8-11]. Industrial robots are mainly employed to replace a human’s role in tasks that are tedious, repetitive and hazardous such as in pick-and-place or manufacturing applications. These are robot manipulators that are highly stiff, heavy, not back-drivable and are mainly for controlling the position of the robot end-effector.

Rehabilitation robots operate close to the human user and should be capable of controlling multiple human joints independently and simultaneously to emulate human tasks. This calls for a robot design that is ergonomic, safe and user friendly. Interaction forces between the human user and the robot should also be considered in controlling the robot in addition to position. The robot needs to not only be capable of moving the user’s limb but also be capable of responding to force exerted by the user’s limb as well. Furthermore, modulation of the interaction must be possible to allow for adjustments of the rehabilitation treatment to suit the patient’s disability characteristics. These requirements introduce a number of challenges in the design and control of robots for rehabilitation:
1.2.1 Design challenges
1. Kinematic compatibility: The robot must conform to the anatomy of the human limb in order to replicate the limb’s motion. The physical human-robot interfaces must only move the limb segment in paths achievable by the human limb.
2. Design optimization: The robot design parameters need to be optimized to obtain a compact and efficient robot that can achieve the range of motion and forces required in rehabilitation without interfering with other parts of the user’s body.
3. Actuators: The desired actuator attributes for a rehabilitation robot are high power to weight ratio, high bandwidth and low acoustic noise which are difficult to achieve.

1.2.2 Control challenges
1. Position control: Position control for robots has typically involved either moving to a target position as fast as possible or moving with a constant velocity. In comparison, the movements of a rehabilitation robot should be smoother and have a velocity trajectory similar to that of normal human movement.
2. Adaptive force control: The robot needs to be capable of interacting and responding to movements generated by the user in real-time. Different types of rehabilitation exercises will require different types of interaction. Furthermore, adjustments to the difficulty or amount of assistance provided during exercises should also be possible to accommodate users with different levels of disability.

1.3 Upper Limb Rehabilitation Robots

Initial rehabilitation robots developed for the human upper limb were end-effector robots that use one physical interface to manipulate the limb, typically at the hand or forearm. End-effector robots can only move the user’s limb in a very limited workspace and cannot independently control each upper limb joint. Due to their lack of kinematic compatibility with the human user, developments soon shifted to exoskeleton robots [12, 13]. Exoskeleton robots have a similar kinematic structure to the human limb and are designed to operate alongside the limb. This exoskeleton approach is further discussed in Chapter 2. Examples of an end-effector and exoskeleton robot are shown in Figures 1.1 and 1.2 respectively.
1.3 Upper Limb Rehabilitation Robots

Figure 1.1: The MIT-MANUS end-effector rehabilitation robot [9].

Figure 1.2: The HAL-5 full-body exoskeleton robot [14].
1.4 Research Objectives

The goal of this research is to identify and attempt to overcome the challenges and limitations in the design and control of an exoskeleton robot for rehabilitation of the upper limb. A new upper limb exoskeleton prototype will be developed while considering the design and control challenges outlined in Section 1.2. The ultimate goal is to develop a multi-purpose robot that can provide automated rehabilitation and assist physiotherapists in providing enhanced rehabilitation processes. The overall research can be divided into the following research objectives:

1.4.1 Modeling and analysis of robot mechanisms for the shoulder joint

The human shoulder joint is undeniably one of the most complex joints in the human body and has an exceptionally large range of motion. This complexity makes designing an exoskeleton robot for this joint a highly challenging task. The anatomy of the upper limb will be studied with a focus on the complex shoulder joint. Past exoskeleton designs will be analyzed and their limitations identified. A novel design of an exoskeleton shoulder mechanism will be proposed to overcome these limitations. This new design is based on a kinematically redundant 4R spherical wrist mechanism which can have a range of possible designs and infinite inverse kinematics solutions. A kinematic model will be developed for the 4R mechanism so that the performance of different designs can be evaluated.

1.4.2 Optimization of the 4R design for an exoskeleton shoulder mechanism

The 4R mechanism will be optimized specifically for use in the shoulder complex of an exoskeleton robot by invoking an evolutionary optimization algorithm. The optimization process will only consider the exoskeleton’s performance when operating in the human shoulder workspace and ignore regions that the shoulder cannot reach. Criteria to evaluate the mechanism’s performance will be identified. Optimization will ensure the redundancy of the 4R mechanism is utilized efficiently to achieve high performance. Furthermore, the kinematic redundancy causes the 4R mechanism to have infinite inverse kinematics solutions therefore the optimization will also involve identifying a set of optimal operating configurations for the mechanism. Hence, an optimal 4R design and a set of optimal operating configurations for this design will be obtained. The 4R design obtained from the optimization process will be analyzed along with other designs to compare the differences in performance.
1.4 Research Objectives

1.4.3 Development of the upper limb exoskeleton system

The optimized 4R mechanism will be used in the development of a complete upper limb exoskeleton system. Using the 4R mechanism will allow the exoskeleton to achieve the full range of motion of the human shoulder with good performance. Due to the large range of motion of the shoulder joint, undesirable mechanical interference between the exoskeleton structure with other parts of the system or with the user’s body can easily occur and therefore will be carefully considered during design. Safety and user friendliness are also critical factors that will be considered in the exoskeleton design to ensure the device is easy to don and can be adjusted for users with different limb lengths. Actuators will be selected according to the performance of a healthy human upper limb. Position and force sensors will be included to provide feedback for control and enable interactive rehabilitation strategies.

1.4.4 Trajectory planning for smooth joint movement

In controlling the position of a rehabilitation robot, it is important to consider the velocities the joint moves with to reach a target position to ensure that a smooth and comfortable motion of the user’s limb is achieved. Velocity profiles of normal human movements will be considered so that human-like movements can be produced. A model of these trajectories will be used to plan smooth trajectories for position control of the exoskeleton joints. In the case of the shoulder where movements of the exoskeleton joints do not translate to similar movements of the user’s shoulder, a smooth trajectory will firstly need to be determined for the desired shoulder movement which will then be converted to the respective trajectories of the exoskeleton joints. Strategies will also be developed to meld a sequence of movements into a single smooth trajectory, allowing for the implementation of task-based movements.

1.4.5 Force-based human-robot interaction

The two main types of interaction between the exoskeleton and the user will involve either the robot or the user controlling limb movement. Controllers will be developed to realize these two interaction types and a combination of both types of interaction will be used to achieve compliant behavior in the exoskeleton. The level of assistance or resistance generated by the exoskeleton will be adjustable to enable accommodation of the rehabilitation treatment for users with different disability conditions. The dynamics of the upper limb and exoskeleton system will be modeled and the effects of friction and gravity will be
compensated for. The controllers will be applied on the exoskeleton with a healthy human subject to validate their performance.

1.5 Thesis Outline

The research work is documented in this thesis in the order of objectives described in the previous section. Including this introduction chapter, the thesis consists of eight chapters in total.

Chapter 2 presents a literature review on recent upper limb exoskeleton robots. This reveals problems with existing exoskeleton designs, particularly for the shoulder joint where the exoskeleton is required to operate near singular configurations and has difficulties achieving the entirety of the human shoulder workspace.

In Chapter 3, the problems of the commonly used 3R spherical wrist for the exoskeleton shoulder mechanism are examined to gain better clarity of its limitations. A novel 4R spherical wrist mechanism is then proposed to overcome these limitations. The kinematics of the redundant 4R spherical wrist is modeled and techniques for forward and inverse kinematics of this redundant mechanism are provided.

This is followed by Chapter 4 which describes the optimization process of the redundant 4R mechanism using the NSGA II algorithm implemented in MATLAB. An optimal 4R design and a set of optimal operating configurations are obtained. The optimization goals include achieving the full workspace of the human shoulder joint without mechanical interference, operating the mechanism far away from singular configurations, and achieving low velocity and feasible 4R joint movements throughout the workspace. An algorithm is developed to identify the optimal operating configurations of the redundant 4R mechanism for reaching 89 points in the shoulder workspace. Arbitrary end-effector points in the workspace can then be determined by interpolating this data. The performance of the optimized 4R design is compared with a common 3R design and an un-optimized 4R design to show the improvements.

The optimized 4R mechanism is used in the design of a complete upper limb exoskeleton system in Chapter 5. Mechanical interference of the exoskeleton is carefully analyzed through simulation of a 3D CAD model in Creo Parametric to ensure the exoskeleton can achieve the required workspace. Key components of the exoskeleton system and features to improve user safety and comfort are presented.
Chapter 6 examines the trajectories in normal human limb movements and uses this to develop an algorithm that generates smooth trajectories for the exoskeleton. These are minimum jerk trajectories which are obtained by minimizing the derivative of acceleration (jerk) over the course of the trajectory. Various strategies are developed to allow a sequence of movements to be combined into a single smooth trajectory.

This is followed by Chapter 7 which discusses the concept of admittance control in which the user moves the exoskeleton and impedance control in which the exoskeleton moves the user’s limb. Modulation of exoskeleton impedance allows an artificial mechanical compliance to be produced. Experimental results are presented for various implementations of these two control strategies.

Finally, Chapter 8 provides conclusions for the overall research work. The contributions of this research are presented and directions for future research are advised.

1.6 Chapter Summary

This chapter discussed the benefits rehabilitation robots can provide to current rehabilitation services. Limitations of conventional rehabilitation methods are identified and robotic devices are suggested as a potential solution. The key challenges in the design and control of rehabilitation robots for the upper limb are highlighted. An exoskeleton-based robot is identified to be the most suitable for providing rehabilitation treatment to the multi-joint upper limb.

The five main objectives of this research work are listed along with a brief overview of how they will be achieved. The first objective is to identify limitations in existing designs of the exoskeleton shoulder mechanism and analyze the proposed solution, a redundant 4R spherical wrist mechanism. This is followed by the optimization of the 4R mechanism design for the specific purpose of generating shoulder movements in an exoskeleton. The optimized design will then be used to develop a complete upper limb exoskeleton system capable of achieving the full spherical range of motion of the human shoulder. An algorithm will be developed to formulate smooth trajectories based on natural human movement for position control of the exoskeleton. Two types of force control strategies will be developed to enable the exoskeleton robot to respond in different ways to user-generated forces.
A comprehensive literature review on upper limb rehabilitation robots is carried out to identify the key issues in their development. Early end-effector rehabilitation robots are briefly introduced followed by a thorough investigation into the recent developments in upper limb exoskeleton robots. The main design requirements and development complications are identified and the various approaches used in past exoskeletons are reviewed. The key issues in current upper limb exoskeletons are discussed which provide the basis for this research work.

2.1 Rehabilitation Robots for the Upper Limb

Early research on rehabilitation robots for the human upper limb was based on end-effector robots. End-effector rehabilitation robots hold the patient’s hand or forearm at one point and generate interaction forces at this sole interface as shown in Figure 2.1a. The kinematic structure of these end-effector robots are based on industrial robots and the kinematics of the human limb are not considered in their design. This type of robot is simpler, easier to fabricate and can be used for patients with different arm lengths. However, determining the posture of the upper limb can be difficult with only one interface, especially if the interface is at the patient’s hand. This is because the upper arm and forearm are
unconstrained and are free to move about the pivots at the shoulder and hand. Controlling the torque at specific upper limb joints is also not possible, resulting in uncontrolled load transfer between upper limb joints. As a consequence, generating isolated movement at a single upper limb joint can be difficult since movement of the robot end-effector can cause a combination of movement at the wrist, elbow and shoulder joints. In addition, the range of motion that can be achieved with end-effector robots tend to be limited therefore only a limited set of rehabilitation movements can be produced. Examples of end-effector rehabilitation robots include the MIT-MANUS [8, 9] (Figure 1.1), the MIME [10, 15] (Figure 2.2) and the GENTLE/s [11] (Figure 2.3). Extensive clinical testing has been done on these devices to evaluate their effectiveness as rehabilitative devices [15-19]. The results indicate reduced motor impairment of the upper limb for patients who received robotic therapy. The positive results justify research on the more sophisticated exoskeleton robots as rehabilitation devices.

Exoskeletons have a structure that resembles the human upper limb, having robot joint axes that match the upper limb joint axes as shown in Figure 2.1b. Exoskeletons are designed to operate alongside the human upper limb, and therefore can be attached to the upper limb at multiple locations. Although this can make it more difficult for the robot to adapt to different arm lengths, multiple interfaces allows the exoskeleton to fully determine the upper limb posture and apply controlled torques to each upper limb joint independently. It is possible for exoskeletons to target specific muscles for training by generating a calculated combination of torques at certain joints. In addition, a larger range of motion is possible compared to end-effector robots which enable a wider variety of movements to be used in rehabilitation exercises.

![Figure 2.1: Kinematics of (a) an end-effector robot and (b) an exoskeleton robot [20].](image-url)
2.2 Movements of the Upper Limb

Operating alongside the human upper limb, exoskeletons need to be capable of producing movements similar to those of the upper limb. The upper limb effectively has a total of 9 degrees of freedom (DOF) from the shoulder to the wrist with the finger joints excluded as shown by \(q_1\) to \(q_9\) in Figure 2.4 [21, 22]. These 9 DOF gives the upper limb exceptionally high maneuverability and allows the hand to reach a very large workspace. The proximal joints of the upper limb are often considered a higher priority for rehabilitation as these joints have the largest influence on the hand’s position and provide support for the rest of the limb.
2.2 Movements of the Upper Limb

The shoulder joint has 5 DOF, 3 rotational DOF which allow spherical rotation of the upper arm and 2 translational DOF which moves the upper arm along the vertical axis and the anterior-posterior axis. The movements of each DOF are commonly described by a pair of terms, one for movement in the positive direction and one for the negative direction:

Shoulder flexion: Rotation of the upper arm about the shoulder instantaneous center of rotation (ICOR) out of the plane of the torso so that it points forwards.

Shoulder extension: Rotation of the upper arm about the shoulder ICOR out of the plane of the torso so that it points backwards.

Shoulder abduction: Rotation of the upper arm about the shoulder ICOR in the plane of the torso so that it is lifted upwards.

Shoulder adduction: Rotation of the upper arm about the shoulder ICOR in the plane of the torso so that it is dropped downwards.

Shoulder medial rotation: Axial rotation of the upper arm towards the torso.

Shoulder lateral rotation: Axial rotation of the upper arm away from the torso.

Shoulder elevation: Translation of the shoulder ICOR upwards.

Shoulder depression: Translation of the shoulder ICOR downwards.

Shoulder protraction: Translation of the shoulder ICOR forwards.

Shoulder retraction: Translation of the shoulder ICOR backwards.

Figure 2.4: 9 DOF of the human upper limb [22].
2.2 Movements of the Upper Limb

An interesting phenomenon of the shoulder is that abduction of the upper arm above the horizontal plane will occur simultaneously with elevation as shown in Figure 2.5 [23]. Without this elevation, abduction above the horizontal plane cannot be achieved.

The elbow joint has 1 rotational DOF which moves the forearm with the following movements:

- **Elbow flexion**: Rotation of the forearm about the elbow joint so that the forearm is moved closer to the upper arm.
- **Elbow extension**: Rotation of the forearm about the elbow joint so that the forearm is moved further from the upper arm.

The wrist joint has 3 rotational DOF allowing the hand to rotate spherically about the wrist joint. The movements are described as:

- **Wrist flexion**: Rotation of the hand about the wrist joint towards the palm.
- **Wrist extension**: Rotation of the hand about the wrist joint away from the palm.
- **Wrist radial deviation**: Rotation of the hand about the wrist joint towards the thumb.
- **Wrist ulnar deviation**: Rotation of the hand about the wrist joint away from the thumb.
- **Forearm pronation**: Rotation of the hand about the axis of the forearm which causes the palm of the hand to face away from the shoulder.
- **Forearm supination**: Rotation of the hand about the axis of the forearm which causes the palm of the hand to face towards the shoulder.

![Figure 2.5: Shoulder elevation during abduction of the upper arm](image-url)
2.3 Recent Upper Limb Exoskeleton Robots

The majority of past upper limb exoskeletons focus on movements for the 3 DOF spherical rotation of the shoulder joint and 1 DOF of the elbow (see Table 2.1). A lower number of exoskeletons have included movements for the 3 DOF wrist joint and even fewer have included movements for the 2 DOF translations of the shoulder joint. One exoskeleton studied during this literature review has also included 1 DOF for grasping movement of the hand. From this, it can be seen that the upper limb DOF that have larger influence on the hand’s position have been the focus of upper limb exoskeletons, i.e. the 3 DOF rotations of the shoulder and 1 DOF of the elbow. Rehabilitation of these movements is of the highest priority since they are the most important in controlling the position of the hand for manipulation tasks.

The ARMin III (Figure 2.6a) [24], MGA [25] (Figure 2.6b) and IntelliArm [26] exoskeletons have implemented an actuated DOF for shoulder elevation & depression. The MEDARM has included actuation for both shoulder elevation & depression and retraction & protraction, allowing 5 DOF of movement at the shoulder complex [27]. Other groups have opted to use passive DOF for these translation movements [26, 28, 29]. Passive DOF allows the joint to move freely but eliminates the ability to generate actuation forces at the joint.

There are a number of commercially available rehabilitation devices for the upper limb. One of the more sophisticated rehabilitation devices available are the Armeo products (Hocoma AG, Switzerland) [30]. These include the 7 DOF ArmeoPower active exoskeleton, ArmeoSpring passive exoskeleton and ArmeoBoom sling suspension system. The ArmeoPower is based on the ARMin III exoskeleton (Figure 2.6a) [24]. Examples of other commercial devices include the mPower arm brace (Myomo, Inc., Cambridge, MA) [31], a 1 DOF portable arm brace which uses electromyography (EMG) signals measured from the biceps and triceps muscles to generate assistive torques for elbow flexion & extension, and the Hand Mentor (Kinetic Muscles, Inc., Tempe AZ) [32], a 1 DOF wearable device for the rehabilitation of the wrist and fingers which provides force, position and EMG feedback and is actuated by an air muscle. The Robot Suit HAL-5 (Cyberdyne Inc., Japan) [14] is a full body exoskeleton for the disabled which uses measured EMG signals to generate assistive torques and empower the user. Examples of commercial end-effector rehabilitation robots include the InMotion robots (Interactive Motion Technologies, Inc., Boston, MA) [33], Biodex System 4 dynamometer (Biodex Medical Systems, Inc., New York) [34], HUMAC NORM (SCMi, Stoughton, MA) [35] and CON-TRES MJ (CMV AG, Switzerland) [36].
<table>
<thead>
<tr>
<th>Exoskeleton Name</th>
<th>Actuated DOF</th>
<th>Shoulder</th>
<th>Elbow</th>
<th>Wrist</th>
<th>Hand</th>
<th>Actuation Method</th>
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<td>Retraction &amp; Protraction</td>
<td>Flexion &amp; Extension</td>
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2.3 Recent Upper Limb Exoskeleton Robots

Figure 2.6: Past upper limb exoskeletons. (a) ARMin III [24]. (b) MGA [25]. (c) CADEN-7 [40]. (d) ABLE [42]. (e) SRE [45, 46]. (f) RUPERT IV [47].
2.3 Recent Upper Limb Exoskeleton Robots

2.3.1 Design of exoskeleton joints

Designing exoskeleton joints that can produce the movements of the upper limb is a challenging task due to the multi-DOF joints of the upper limb and the limited space available for the exoskeleton structure. The 3 DOF spherical movement of the shoulder is most commonly implemented using a 3-revolute (3R) spherical wrist mechanism surrounding the shoulder [24-27, 37, 40, 51]. This includes three revolute joints that always maintain alignment with the shoulder ICOR during operation. These joints are positioned a distance away from the shoulder and are responsible for moving the shoulder in flexion & extension, abduction & adduction and medial & lateral rotation movements. Several exoskeletons have designed the distal third joint as a circular rail surrounding the user’s upper arm [24, 28, 37, 40, 47]. This reduces the space required for the moving 3R links and increases the workspace of the exoskeleton. The 3R mechanism will be analyzed in Chapter 3. The exoskeleton elbow joint is implemented using a single revolute joint aligned with the human elbow joint. For the 3 DOF human wrist joint, the 3R mechanism is used [28, 40].

2.3.2 Kinematic singularities in upper limb exoskeletons

Serial robots with multiple rotary joints may possess configurations that cause one DOF to be lost. This occurs in configurations where the axes of two rotary joints align with each other. In past upper limb exoskeletons, singularities occur in postures where two joints of the shoulder 3R spherical wrist mechanism align and when the upper arm medial & lateral rotation axis aligns with the forearm pronation & supination axis at full elbow extension [40]. The latter is less problematic since the human upper limb also has the same singularity. This can be overcome by physically constraining both the upper arm and forearm to their respective links on the exoskeleton so that upper arm medial & lateral rotation can be differentiated from forearm pronation & supination. However, in the other occurrence of singular configuration, the 3 DOF spherical shoulder joint does not have the singularity that occurs in the 3R mechanism of the exoskeleton. Therefore, the exoskeleton will have problems operating near the singular configurations while the human shoulder does not. Operating near a singular configuration will require high exoskeleton joint velocities to produce small movements of the shoulder. It is not possible to avoid operating near singularities of the 3R mechanism as the range of motion of the human shoulder is too large. The CADEN-7 [40], MGA [25] and MEDARM [27] exoskeletons have been designed so that the singular configurations of the 3R mechanism occur at postures that are less likely to interfere with performing rehabilitation movements.
2.3 Recent Upper Limb Exoskeleton Robots

2.3.3 Joint alignment

Misalignment between the exoskeleton and the human limb can cause several problems such as the generation of undesirable interaction forces and inaccurate positioning of the limb. To align the exoskeleton joints with their respective limb joints, past exoskeletons have been designed with linear joints that can be used to manually adjust the length of the exoskeleton link. Some research groups have used redundant passive joints that are free to translate and rotate [26, 28, 29]. By using these passive joints in the exoskeleton structure, the interaction forces caused by misalignment will adjust the structure to minimize the misalignment. In other words, the exoskeleton structure automatically self-corrects the misalignment. As mentioned in Section 2.3, several groups have used redundant passive joints for the translational movements of the shoulder joint. The redundant joint aligns the ICOR of the exoskeleton’s shoulder mechanism with the ICOR of the user’s shoulder joint during translation movements. However, force generation for the translation movements is not possible using this method due to its passive nature. A major drawback of using passive joints for self-alignment is that the user is required to carry the weight of the exoskeleton structure. This is not desirable in a rehabilitation exoskeleton.

Apart from correcting misalignment, redundant joints can be used for other purposes. Using additional joints in an exoskeleton can provide a solution for the mechanical singularity problem, reduce joint speeds during motion, and allow adjustments of the robot’s size to fit the user [52].

2.3.4 Human-robot interfaces

The most important human-robot interface (HRI) in an exoskeleton is the physical coupling between the exoskeleton and the user’s upper limb. These HRI allow the exoskeleton to transmit forces to the user’s limb so that movements and interaction forces can be generated.

Apart from physical HRI, several other methods of interaction between the user and an exoskeleton have also been explored. EMG signals provide an indication of muscle activation and can be measured using surface electrodes attached onto the skin above the muscles. EMG signals has been used in several upper limb exoskeletons [53-59].

Vision sensors have been used in the control of assistive exoskeletons. Kiguchi et al. worked on an assistive exoskeleton that modifies the user’s motion based on environmental information obtained from sonar sensors and stereo cameras [60]. Baklouti et al. proposed the use of face and mouth gestures as control commands for an exoskeleton [61].
Providing haptic feedback to the user through touch sensations has also been considered. Kapur et al. have used vibration actuators to generate sensations at different points on the user’s arm to guide it through rehabilitation movements [62]. De Rossi et al. have been developing wearable garments using electroactive polymers that allow strain sensing and actuation [63].

2.3.5 Actuation

The majority of existing exoskeletons are actuated by electric motors. Recently, there has been increased interest in the use of pneumatic muscle actuators (PMA). PMA can only generate tension force through contraction therefore a pair is often used for each DOF to generate bi-directional movement [64]. PMA has several advantages over electric motors with the most significant being its high power-to-weight ratio. In addition, the soft nature of PMA makes the exoskeleton compliant and inherently safer to use. However, PMA exhibit non-linear actuation characteristics making them more difficult to control. The use of compressed air as a power source is inconvenient and the compressor and valves are noisy during operation. They also have a relatively low bandwidth which limit the rate at which they can respond to command signals. Caldwell et al. have found that the bandwidth can be increased several folds by reducing the dead volume inside the PMA by the addition of filler materials and ensuring effective air flow [65]. Several upper limb exoskeletons in literature have used PMA [45, 47, 66]. The lightweight RUPERT IV exoskeleton (Figure 2.6f) is a portable exoskeleton that uses unpaired PMA to provide movement for 5 DOF of the upper limb [47]. However, the joints can only be actuated in one direction since only one PMA is used for each DOF. The commercially available Hand Mentor uses a PMA for actuating wrist flexion & extension movement.

Passive exoskeletons use actuators that are only able to generate resistive force. These exoskeletons have a lower weight than motor-actuated active exoskeletons and are inherently safe. However, passive exoskeletons cannot actively assist movement so they are limited to providing resistive exercises and gravity balancing. The Dampace exoskeleton is an example of a passive robot which uses hydraulic disk brakes to generate resistive torques for rehabilitation training [49]. The WREX uses springs to negate the effects of gravity so that the patient can move the arm with reduced effort [50].
2.3 Recent Upper Limb Exoskeleton Robots

2.3.6 Exoskeleton control

Effective control strategies are necessary for the exoskeleton to operate harmoniously with the human limb. Common strategies include position control and impedance control [25, 28, 39, 67, 68]. Several exoskeletons have also used admittance control [25, 68]. Many devices have accounted for the effects of gravitational and frictional forces with gravity and friction compensation controllers [24, 25, 39, 43, 49]. Rahman and Kiguchi et al. used PD control for their exoskeleton’s passive mode while using a neuro-fuzzy based biological controller for active assist mode [53]. Rahman et al. have used nonlinear computed torque control [41] and nonlinear sliding mode control [69] for trajectory tracking of the ExoRob exoskeleton. A bio-inspired controller based on the equilibrium point hypothesis (EPH) has been proposed for the NEUROexos exoskeleton [70, 71]. The EPH, also known as the $\lambda$ model for motor control, suggests that human motion involves a constantly shifting equilibrium position along the desired movement trajectory [72].

The RUPERT IV exoskeleton invoked an iterative learning controller to overcome the highly non-linear nature of the PMA actuators and the patient’s limb as well as to adapt to different subjects for performing different reaching tasks in passive therapy mode [47]. Adaptive control algorithms have also been used for the MIT-MANUS [9] and ARM Guide [73] end-effector robots to adapt the device to the user’s ability in order to provide a training task of appropriate difficulty.

Several research groups have used EMG signals for the control of an exoskeleton [53-56]. There are also commercially available exoskeleton-type devices that use EMG for control, including the mPower, Hand Mentor and Robot Suit HAL-5. Ando et al. have used EMG signals to identify voluntary movement from a tremor patient to control an exoskeleton [57]. EMG signals have also been used to estimate the dynamics of the limb [58, 59]. This information can be useful in creating a unique model of the user’s limb.

Measurements of EMG signals vary between individuals and can also vary on the same person due to offsets in electrode placement, fatigue and other factors [74]. As such, adaptive strategies and effective design and placement of the electrodes are required to account for these variations. A few researchers have used adaptive control strategies for EMG signal control of an upper limb exoskeleton. Kiguchi et al. have worked on several EMG controlled exoskeletons. One example is the 3 DOF W-EXOS upper limb motion assist exoskeleton which adapts to the changing EMG signal levels of users with a fuzzy-neuro control method [56]. Perry et al. also used a method to adapt an EMG controlled exoskeleton to different
users [55]. In this case, genetic algorithm was used to optimize the parameters of Hill-based muscle models called Myoprocessors.

### 2.4 Discussion

Recent technological advances have enabled the development of feasible exoskeleton robots. Modeling software has allowed exoskeletons to be tested in simulations before they are fabricated, allowing rapid prototype development. Biomechanics modeling allow the exoskeleton to mimic the dynamics of the human limb. Sensor technologies, control strategies and computing power have advanced to the extent where they are no longer major obstacles. However, actuator and power supply technologies still have limitations. Current actuators are unable to provide both a high power-to-weight ratio and high bandwidth while modern power supplies have insufficient energy density. PMA has a high power-to-weight ratio but lack bandwidth while motors have sufficient bandwidth but have a poor power-to-weight ratio. Current mobile exoskeleton robots rely on a lower limb exoskeleton to carry the weight of the actuators and power supply. Although, this has been shown to be a feasible approach with the recent success of the full-body HAL-5 exoskeleton for assisting the elderly and physically weak [75], improvements on the weight and efficiency of actuators and power supplies are still needed to achieve better mobility and lighter exoskeletons.

One of the fundamental limitations in past upper limb exoskeletons is the inability of the shoulder mechanism to achieve the entire human shoulder workspace with adequate performance. This is due to the singular configurations present in the 3R spherical wrist mechanism that are used in the shoulder complex of the exoskeletons. Operating at a singular configuration results in the loss of 1 DOF in the 3R mechanism and therefore the exoskeleton becomes unable to achieve the same movements as that of the 3 DOF spherical shoulder. Even operating near a singular configuration reduces the ability of the 3R mechanism to rotate about the affected DOF and requires the 3R mechanism to move at undesirably high velocities. Several recent upper limb exoskeletons have considered this problem and designed the exoskeleton so that the singular configurations occur at uncommon shoulder postures at the edge of the shoulder workspace [25, 27, 40, 76]. Although this change partially improves the performance of the exoskeleton, the singular configurations are still present in the shoulder workspace and operating near these configurations causes poor performance in the 3R mechanism.
Among the 9 DOF in the human upper limb, the 3 DOF spherical movement of the shoulder has the largest range of motion and has the most influence on the rest of the upper limb since it is the most proximal joint in the limb. Therefore, recovery of the shoulder joint is often more urgent than the other joints in the upper limb. The shoulder joint is also highly complex and is the most powerful joint in the upper limb making it the most difficult joint to provide rehabilitation for. Thus, designing an exoskeleton that is capable of implementing all movements of a normal human shoulder is highly challenging but such capabilities can provide significant improvements to existing shoulder rehabilitation methods.

Clinical results are available for some of the early end-effector type robots which provide strong evidence that robotic rehabilitation has a beneficial effect on motor function [77]. However, comparing clinical data is rather difficult since different groups use different devices, control strategies, intervention strategies and assessment criteria. There are many patient specific parameters that can affect the outcome of the treatment which may also need to be taken into consideration. There are currently insufficient guidelines and tools used in clinical evaluations of robotic rehabilitation, and to some degree in conventional rehabilitation, which is limiting the amount of quality data that can be acquired [12]. Many assessment methods, such as the assessment of posture, are based on subjective impressions [78] which makes it difficult to justify the effectiveness of rehabilitation treatments. Future research will need to focus on developing and refining these guidelines and tools to ensure researchers can get as much reliable data as possible out of clinical evaluations. With better data, the effects of variations in the rehabilitation treatment and in the patient’s condition on motor and functional recovery can be better understood. This will enable the development of more effective rehabilitation exoskeletons and intervention strategies. Exoskeleton technologies have the potential to initiate new areas of research as well as support existing research work. New approaches to rehabilitation treatment and patient assessment may be discovered and a better understanding of the human neuromuscular system can be achieved.

One promising approach for patient treatment is the application of task-based exercises in rehabilitation. There is evidence that suggests task-based rehabilitation specifically designed to deal with lost abilities produce better results than resistance strengthening exercises [4]. However, realistic task-based exercises are difficult to achieve with manual rehabilitation methods. Exoskeletons have the ability to accurately control multiple joints at the same time, enabling them to produce more realistic task-based exercises for the patient. In addition, studies have found that rehabilitation is more effective when the patient exerts voluntary effort [79] in intensive and frequent exercises [4], much like recreational exercises.
Incorporating rehabilitation exercises into virtual games can make rehabilitation more enjoyable thus motivating the patient to put in effort and encouraging more exercise. In addition, the use of virtual reality enables more realistic task-based exercises to be performed. The concept of using virtual games to provide therapy exercises has already been applied in a number of exoskeletons [20, 25, 49, 67, 68]. The next step is to design games based on rehabilitation principles and allow the games to be adjusted to better match the patient’s level of motor deficiency.

2.5 Chapter Summary

This chapter presented a comprehensive review on past upper limb rehabilitation robots. Numerous issues in the development of upper limb exoskeleton robots for rehabilitation have been identified and there is much room for improvement. Of particular concern is the inability of the exoskeletons to achieve the full range of motion of the shoulder’s spherical movement with adequate performance. This is a major limiting factor as the exoskeletons cannot perform the same movements as that of a healthy shoulder joint and therefore the movements that can be used in rehabilitation are limited. The limitation of this key upper limb joint hinders other advancements such as the development of task-based rehabilitation exercises and objective evaluation strategies for assessing the upper limb’s neuromuscular condition. This major limitation provides the basis for this research.
Upper limb exoskeletons developed in the past have major limitations in the shoulder mechanism which cause restrictions in shoulder movement and prevent the exoskeleton from achieving the entire spherical range of motion of the human shoulder. In order to design a shoulder exoskeleton that can overcome these limitations and operate effectively with the human upper arm, the human shoulder and the spherical wrist mechanism commonly used in past exoskeletons are analyzed.

This chapter presents the new concept of a 4-revolute (4R) spherical wrist mechanism for a shoulder exoskeleton. A brief description of the shoulder joint anatomy is firstly provided to gain an understanding of the shoulder’s motions. The 3R spherical wrist mechanism typically used in past shoulder exoskeletons is analyzed and the major limitations in using this mechanism are highlighted. The kinematically redundant 4R mechanism is then proposed to overcome these limitations. The kinematics of this redundant mechanism is modeled for the right human shoulder and methods for solving the forward kinematics and inverse kinematics problems are presented.
3.1 Anatomy of the Human Upper Limb

The human upper limb can be considered a serial manipulator with three segments connected through three joints. The wrist joint connects the hand to the forearm, the elbow joint connects the forearm to the upper arm and the shoulder joint connects the upper arm to the torso. Combined, the upper limb can be modeled as a serial manipulator with 9 DOF from the shoulder to the wrist [22] (see Figure 2.4). The wrist joint is modeled as three revolute joints intersecting at one point yielding a 3 DOF spherical joint. The elbow joint is modeled as a simple 1 DOF hinge joint. The shoulder joint is modeled using 5 DOF and its anatomy will be discussed below. Since this research focuses primarily on developing an exoskeleton for the shoulder joint, details on the wrist and elbow joints are omitted.

3.1.1 The human shoulder

The human shoulder joint is one of the most complex joints in the human skeleton and is fundamentally a mechanism consisting of three joints, the glenohumeral, the sternoclavicular and the acromioclavicular joints [21, 22] as shown in Figure 3.1. These three joints allow the upper arm to move with extraordinary mobility over a large range of motion.

The glenohumeral joint is the main joint in the shoulder and is what the generic term “shoulder joint” often refers to. This is a ball and socket joint which allows the upper arm to revolve in two dimensions about the pivot at the ICOR and also allows the upper arm to rotate about its axis. It is formed by the articulation between the head of the humerus which is the “ball” and the glenoid fossa of the scapula which is the “socket”. The connection between these two bones is relatively small due to the shallowness of the glenoid fossa which gives the joint its tremendous mobility. The humeral head is held against the glenoid fossa by the rotator cuff muscles.

The movements of the two remaining joints, the sternoclavicular and the acromioclavicular joints, are much smaller compared to the glenohumeral joint. The sternoclavicular joint articulates the medial end of the clavicle onto the manubrium at the top of the sternum. The acromioclavicular joint is formed by the articulation between the acromion of the scapula and the distal end of the clavicle. These two joints cause translations of the glenohumeral head and also increase the rotational range of motion of the shoulder. Motions of the humerus involve the simultaneous motions of the glenohumeral, acromioclavicular and sternoclavicular joints [80]. An example of this simultaneous movement is in the shoulder abduction movement shown in Figure 3.2.
In the kinematics sense, the movements of all three joints (the glenohumeral, sternoclavicular and acromioclavicular joints) can be combined and simplified into 5 DOF [22]. This includes 3 DOF for the spherical and axial rotation of the upper arm about the shoulder ICOR and 2 DOF for the translations of the ICOR along the vertical axis and along the anterior-posterior axis. The 3 DOF of rotational motion are commonly referred to as shoulder abduction & adduction, flexion & extension, and medial & lateral rotation. The 2 DOF of translational motion are referred to as elevation & depression and retraction & protraction. These 5 DOF of the shoulder are illustrated in Figure 3.3.

Independently moving the 2 translational DOF with an exoskeleton is particularly challenging as the user’s torso, shoulder and upper arm must be rigidly attached to the exoskeleton. Furthermore, shifts in the user’s body posture can cause relatively large inaccuracies in translation movements of the shoulder. In this research, the 2 translational DOF of the shoulder are not considered in the exoskeleton design. Exclusion of these 2 DOF do not cause significant issues since the range of motion of these DOF are relatively small and full shoulder rotation can still be achieved. Even if the exoskeleton does not have these DOF, small shoulder translations can still be achieved due to the softness of the strap and human tissue. Shoulder translations are also less important compared to shoulder rotations in manipulation tasks.

Figure 3.1: Anatomy of the human shoulder. The three joints responsible for shoulder movements are the glenohumeral, sternoclavicular and acromioclavicular joints.
3.1 Anatomy of the Human Upper Limb

Figure 3.2: Shoulder abduction requires simultaneous movement of the glenohumeral, sternoclavicular and acromioclavicular joints [80]. It can be seen that the clavicle, scapula and humerus all move during abduction.

Figure 3.3: Movements of the 5 DOF shoulder joint.
3.2 Spherical Wrist Mechanism for the Exoskeleton Shoulder

An exoskeleton has a kinematic structure that resembles the human limb, with robot joint axes that align with the limb joint axes. This robot is designed to operate side-by-side with the human upper limb and therefore must produce movements similar to the human counterpart. The human shoulder joint is one of the most complex joints in the human body and designing an exoskeleton for this joint is a challenging task. The shoulder joint has a very large range of motion, capable of rotating the upper arm in 3 DOF in a spherical motion over approximately half of the entire spherical workspace, i.e. the upper arm has a semi-spherical workspace.

Hence, a shoulder exoskeleton is also required to have 3 DOF of spherical motion. However, it is not feasible to implement a true ball-and-socket spherical joint for an active exoskeleton as it cannot be aligned with the user’s shoulder joint and is difficult to actuate. Therefore, exoskeletons in the past use a 3R spherical wrist mechanism often with 90° links to replicate the spherical movement \[24-27, \ 40, \ 51\]. Most shoulder exoskeletons have a structure similar to that shown in Figure 3.4, where the most distal joint (Joint 3) is incorporated into a revolving mechanism around the upper arm. However, the 3R mechanism behaves like a gimbal and consequently possesses problematic singular configurations \[40, \ 76\]. These singular configurations occur when the axes of rotation of two rotary joints align with each other, resulting in the loss of one DOF. The human shoulder joint behaves like a spherical joint which does not possess any singular configurations and therefore does not experience this problem. The 3R mechanism, however, has two distinct singular configurations which occur when the axis of rotation of the base joint (Joint 1) align with the axis of rotation of the distal joint (Joint 3). One singular configuration occurs when the axis of Joint 3 is in the same direction as the axis of Joint 1. The second singular configuration occurs when the axis of Joint 3 is 180° opposite to that of the first configuration as shown in Figure 3.4. The human shoulder is capable of reaching approximately half of the spherical workspace therefore at least one of the two singular configurations will occur inside or near the edge of the shoulder workspace no matter how the 3R mechanism is positioned. In other words, the singular configuration of the 3R mechanism cannot be adequately avoided if the exoskeleton is to operate in the entire workspace of the human shoulder joint.
When the 3R mechanism approaches a singular configuration, the mechanism has difficulty performing rotations about the axis that is lost. A slow rotation of the shoulder about the affected axis requires high velocities from the 3R joints. The worst case is when two of the 3R joints completely align with one another, i.e. a singular configuration occurs. In this situation, the 3R mechanism needs to change its configuration instantaneously in order to produce smooth shoulder rotations about the lost axis (see Figure 3.5). This is not possible in practice as there will always be a time delay to move the 3R mechanism into the necessary configuration. This causes the exoskeleton to produce jerky movements which can hinder the user’s shoulder movement and can cause injuries or discomfort. In addition, the attempt to achieve this instantaneous change of configuration causes the 3R mechanism to generate very high accelerations and velocities. This will increase tracking errors, increase the risk of injury, intimidate the user and require the 3R exoskeleton to be constructed with costly high performance components.

The design shown in Figure 3.4 is the simplest design of the 3R exoskeleton with the base joint of the 3R mechanism positioned directly behind the shoulder. However, this exoskeleton design has a very limited range of motion due to the limited space available for the movement of the mechanism’s links. It is not possible for this exoskeleton to raise the user’s upper arm above the horizontal plane as this will cause part of the 3R mechanism to collide with the user’s head. This problem is illustrated in Figure 3.6.
3.2 Spherical Wrist Mechanism for the Exoskeleton Shoulder

Figure 3.5: A 3R exoskeleton moves into a singular configuration shown in the top right figure where the axis of rotation of Joint 3 aligns with the axis of rotation of Joint 1. In this configuration, the exoskeleton cannot produce horizontal flexion and extension of the shoulder unless Joint 1 is adjusted into the position shown in the bottom right figure.
3.2 Spherical Wrist Mechanism for the Exoskeleton Shoulder

Figure 3.6: A 3R exoskeleton with the base joint behind the shoulder cannot raise the upper arm above the horizontal plane as this will cause the mechanism to collide with the user’s head.

In an attempt to minimize the negative effects of singular configurations on shoulder movements, some exoskeletons were designed to have the singular configurations of the 3R mechanism occur at postures that are less likely to interfere with performing rehabilitation exercises [25, 27, 40]. This is done by moving the base joint (and consequently the singular configuration) of the 3R mechanism laterally so that it is in the position shown in Figure 3.7. However, even if the exoskeleton does not operate exactly at the singular configuration, it will still experience a decrease in performance when it operates nearby. The 3R mechanism with a 45° lateral offset of the base joint can achieve a larger range of motion than the simpler design in Figure 3.4 as it is possible to raise the user’s arm above the horizontal plane. However, the 3R mechanism will still move dangerously close to the user’s head when the upper arm is raised above the horizontal plane as shown in Figure: 3.9. In addition, raising the upper arm backwards will make the arm dangerously close to the base joint of the 3R mechanism as shown in Figure: 3.8.

Furthermore, the 3R exoskeleton requires a large circular rail in order to achieve full range of motion of shoulder axial rotation throughout the workspace. A large circular rail is required because of the difference in angular position drift between the exoskeleton joint and the user’s shoulder axial rotation as the end-effector moves through the workspace. The use of a large circular rail makes the exoskeleton more difficult for the user to don and it can interfere with the user’s torso when the arm is lowered. A thin circular rail is desirable however this is challenging to achieve.
3.2 Spherical Wrist Mechanism for the Exoskeleton Shoulder

Figure 3.7: The 3R exoskeleton design with the base joint offset laterally by 45° from behind the shoulder.

Figure 3.8: The upper arm can move dangerously close to the shifted base joint.
Figure 3.9: A 3R exoskeleton with the base joint shifted 45° laterally from behind the shoulder will operate dangerously close to the user’s head when raising the upper arm above the horizontal plane.
3.2 Spherical Wrist Mechanism for the Exoskeleton Shoulder

It is possible to avoid the singular configurations and keep the mechanism away from potential collisions if a redundant joint is introduced into the 3R mechanism. The resulting 4R spherical wrist mechanism (Figure 3.10) has one redundant joint which can be used to keep the system away from singular configurations. This 4R spherical wrist concept has been considered for generic robot manipulators in the past [81-84] but it has not been utilized in the design of an exoskeleton’s shoulder mechanism. This mechanism has been used in limited studies, possibly because there are better alternatives to using a replicated spherical joint for a generic robot manipulator. A shoulder exoskeleton, however, has very limited joint design possibilities due to the workspace constraints and the necessity to replicate the shoulder’s spherical movements. In this case, a 4R mechanism is very suitable. In this research, the 4R mechanism is considered for the design of an upper limb exoskeleton’s shoulder complex.

![Figure 3.10: The 4R shoulder mechanism concept.](image-url)
3.3 The 4R Mechanism

The 4R mechanism has four revolute joints and is therefore considered a 4 DOF robot. However, the 4R mechanism is only capable of moving the end-effector in 3 DOF of spherical motion about the ICOR. Hence, the 4R mechanism can be described as a 4 DOF redundant robot with 3 DOF of spherical motion. This kinematic redundancy is required to avoid singular configurations of the mechanism and prevent mechanical interference with the user while achieving the entire shoulder workspace.

The fundamental 4R mechanism consists of a stationary base, an end-effector and three links \((L_1, L_2, L_3)\) connected in series through four revolute joints \((\theta_1, \theta_2, \theta_3, \theta_4)\) as shown in Figure 3.11. Each of the four revolute joints has an axis of rotation that intersects with the ICOR. The joints are positioned a suitable distance away from the ICOR so that they do not interfere with the user’s shoulder. This allows the 4R mechanism to operate alongside the human upper arm and mimic the spherical movements of the human shoulder joint. Due to the characteristics of the mechanism design, the position and orientation of the end-effector directly reflects the posture of the user’s upper arm.

The following terms are used to describe the various aspects of this mechanism:

**ICOR:** The center of spherical rotation. All joints of the 4R mechanism intersect at this point. The ICOR of the 4R coincides with the ICOR of the human shoulder joint.

**Link angle \((\alpha)\):** The angle between the two joints in the arc-shaped link about the ICOR.

**Joint angle/angular position \((\theta)\):** The angle of rotational displacement of the revolute joint from the default position.

**Joint/end-effector position:** The location of the joint/end-effector with respect to the ICOR.

**Joint configuration:** A combination of joint positions that achieves a certain end-effector position.

3.4 Kinematic Modeling of the 4R Mechanism

The kinematics of the multi-link 4R mechanism is modeled using the Denavit-Hartenberg (DH) notation [85]. The main advantage of the DH notation is that only four parameters are required for each joint whereas six parameters are normally required for the 6 DOF of a rigid body in 3D space. This is made possible by kinematic constraints present in the two types of
1 DOF robotic joints that can be used in a serial manipulator, the revolute joint and the prismatic joint. Kinematic analysis is therefore simpler and computational cost is reduced.

In the DH notation, a Cartesian coordinate system is assigned to each robot joint while following a set of rules. The coordinate systems are numbered from 0 to \( n \) starting from the base joint and ending at the end-effector. The \( z \)-axis \( (Z_i) \) is assigned so that it is aligned with the axis of motion of joint \( i \). In the case of revolute joints, the \( z \)-axis is aligned with the axis of rotation. The \( x \)-axis \( (X_i) \) is assigned so that it is parallel to the common normal of the \( z \)-axes in the current and previous coordinate systems \( (Z_i \) and \( Z_{i-1} \)). If \( Z_i \) and \( Z_{i-1} \) are parallel, then there is no unique common normal. In this case, \( X_i \) is in the direction from \( Z_{i-1} \) to \( Z_i \). Finally, the \( y \)-axis \( (Y_i) \) is assigned by using the right-handed coordinate system.

A transformation between the coordinate systems of two consecutive joints in a serial robot is described by one transformation associated with the joint \( [J] \), and a second transformation associated with the link \( [L] \). The coordinate transformation along a serial robot is then a sequence of these transformations. For a robot with \( n \) links the complete kinematics equation of the robot is given by (3.1) where \( [T] \) is the transformation from the base joint to the end-effector.

\[
[T] = [J_1][L_1][J_2][L_2] \cdots [J_n][L_n] \tag{3.1}
\]

![Figure 3.11: Parameters of the 4R mechanism.](image-url)
By defining the coordinate systems using the DH notation outlined above, the transformations can be defined by (3.2) and (3.3) where $\theta_i$ is the angle about $Z_{i-1}$ from $X_{i-1}$ to $X_i$ and is the joint variable if joint $i$ is rotary; $d_i$ is the distance along $Z_{i-1}$ from the origin of the $(i-1)$th coordinate system to the common normal of $Z_{i-1}$ and $Z_i$ and is the joint variable if joint $i$ is prismatic; $a_i$ is the length of the common normal of $Z_{i-1}$ and $Z_i$ from the $Z_{i-1}$ axis to the $Z_i$ axis; and $\alpha_i$ is the angle about the common normal of $Z_{i-1}$ and $Z_i$ from the $Z_{i-1}$ axis to the $Z_i$ axis.

$$[J_i] = \begin{bmatrix} \cos \theta_i & -\sin \theta_i & 0 & 0 \\ \sin \theta_i & \cos \theta_i & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.2}$$

$$[L_i] = \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & \cos \alpha_i & -\sin \alpha_i & 0 \\ 0 & \sin \alpha_i & \cos \alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.3}$$

These transformations are a sequence of translations and rotations where:

$$[J_i] = \text{Trans}_{j_i}(d_i) \text{ Rot}_{j_i}(\theta_i) \tag{3.4}$$

$$[L_i] = \text{Trans}_{L_i}(a_i) \text{ Rot}_{L_i}(\alpha_i) \tag{3.5}$$

$$\text{Trans}_{j_i}(d_i) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.6}$$

$$\text{Rot}_{j_i}(\theta_i) = \begin{bmatrix} \cos \theta_i & -\sin \theta_i & 0 & 0 \\ \sin \theta_i & \cos \theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.7}$$

$$\text{Trans}_{L_i}(a_i) = \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.8}$$

$$\text{Rot}_{L_i}(\alpha_i) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \alpha_i & -\sin \alpha_i & 0 \\ 0 & \sin \alpha_i & \cos \alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.9}$$

The coordinate systems of two consecutive joints are related by:

$$T_{i-1}^i = [J_i][L_i] \tag{3.10}$$
This gives the DH transformation matrix as:

\[
T_{i}^{i-1} = \begin{bmatrix}
\cos \theta_i & -\cos \alpha_i \sin \theta_i & \sin \alpha_i \sin \theta_i & a_i \cos \theta_i \\
\sin \theta_i & \cos \alpha_i \cos \theta_i & -\sin \alpha_i \cos \theta_i & a_i \sin \theta_i \\
0 & \sin \alpha_i & \cos \alpha_i & d_i \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  \hspace{1cm} (3.11)

To interpret the transformation, the matrix can be represented as (3.12) where \( R \) is the \( 3 \times 3 \) rotation matrix (3.13) which represents the relative orientation between the two coordinate systems (i.e. relates the \( X_i, Y_i, Z_i \) axes with the \( X_{i-1}, Y_{i-1}, Z_{i-1} \) axes) and \( r \) is the \( 3 \times 1 \) translation vector (3.14) which represents the relative position between the two coordinate systems.

\[
T = \begin{bmatrix} R & r \\ 0 & 1 \end{bmatrix}
\]  \hspace{1cm} (3.12)

\[
R = \begin{bmatrix} n_x & o_x & a_x \\ n_y & o_y & a_y \\ n_z & o_z & a_z \end{bmatrix} = \begin{bmatrix}
\cos \theta_i & -\cos \alpha_i \sin \theta_i & \sin \alpha_i \sin \theta_i \\
\sin \theta_i & \cos \alpha_i \cos \theta_i & -\sin \alpha_i \cos \theta_i \\
0 & \sin \alpha_i & \cos \alpha_i
\end{bmatrix}
\]  \hspace{1cm} (3.13)

\[
r = \begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix} = \begin{bmatrix} a_i \cos \theta_i \\ a_i \sin \theta_i \\ d_i \end{bmatrix}
\]  \hspace{1cm} (3.14)

Transformation into subsequent coordinate systems is achieved by combining the transformation matrices between each successive coordinate system using (3.15). This allows the determination of the relative position and orientation of any subsequent coordinate system with respect to a previous reference coordinate system and vice versa.

\[
T_i^0 = T_i^1 T_i^2 \ldots T_i^{i-1}
\]  \hspace{1cm} (3.15)

The global coordinate system is located at the ICOR of the right shoulder with the x-axis pointing to the right, y-axis pointing forward and z-axis pointing upward with respect to the user. A coordinate system is defined for each subsequent joint using the DH notation. For simplicity, the coordinate system of each joint is defined with an origin at the ICOR of the 4R mechanism, i.e. the length parameters \( a_i \) and \( d_i \) for all \( i \) are zero. This is acceptable because the axis of rotation of all the joints in the 4R mechanism always intersect at the ICOR. As a result, the occurrence of singular configurations is dependent on only the orientation of the joints and independent of the distance between the joints and the ICOR. The DH parameters for the 4R mechanism are shown in Table 3.1. Note that the first line of parameters is used to define the orientation of the base joint with respect to the global coordinate system. Therefore, numbering of the DH parameters in Table 3.1 is delayed by one.
The DH parameters of the 4R mechanism are used to obtain the transformation matrices that represent the geometric relationship between each pair of adjacent coordinate systems:

\[ T_1^0 = \begin{bmatrix}
\cos \phi_z & -\cos \phi_x \sin \phi_z & \sin \phi_x \sin \phi_z & 0 \\
\sin \phi_z & \cos \phi_x \cos \phi_z & -\sin \phi_x \cos \phi_z & 0 \\
0 & \sin \phi_x & \cos \phi_x & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \]  
(3.16)

\[ T_2^1 = \begin{bmatrix}
\cos \theta_1 & -\cos \alpha_1 \sin \theta_1 & -\sin \alpha_1 \sin \theta_1 & 0 \\
\sin \theta_1 & \cos \alpha_1 \cos \theta_1 & \sin \alpha_1 \cos \theta_1 & 0 \\
0 & -\sin \alpha_1 & \cos \alpha_1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \]  
(3.17)

\[ T_3^2 = \begin{bmatrix}
\cos \theta_2 & -\cos \alpha_2 \sin \theta_2 & \sin \alpha_2 \sin \theta_2 & 0 \\
\sin \theta_2 & \cos \alpha_2 \cos \theta_2 & -\sin \alpha_2 \cos \theta_2 & 0 \\
0 & \sin \alpha_2 & \cos \alpha_2 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \]  
(3.18)

\[ T_4^3 = \begin{bmatrix}
\cos \theta_3 & -\cos \alpha_3 \sin \theta_3 & \sin \alpha_3 \sin \theta_3 & 0 \\
\sin \theta_3 & \cos \alpha_3 \cos \theta_3 & -\sin \alpha_3 \cos \theta_3 & 0 \\
0 & \sin \alpha_3 & \cos \alpha_3 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \]  
(3.19)

\[ T_5^4 = \begin{bmatrix}
\cos \theta_4 & -\sin \theta_4 & 0 & 0 \\
\sin \theta_4 & \cos \theta_4 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \]  
(3.20)

These transformation matrices are used to transform coordinates between the various coordinate systems in the 4R mechanism.

**Table 3.1: DH parameters of the 4R robot**

<table>
<thead>
<tr>
<th>Link $i$</th>
<th>$a_i$</th>
<th>$\alpha_i$</th>
<th>$d_i$</th>
<th>$\theta_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>$\phi_x$</td>
<td>0</td>
<td>$\phi_z$</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>$-\alpha_1$</td>
<td>0</td>
<td>$\theta_1$</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>$\alpha_2$</td>
<td>0</td>
<td>$\theta_2$</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>$\alpha_3$</td>
<td>0</td>
<td>$\theta_3$</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\theta_4$</td>
</tr>
</tbody>
</table>
3.5 Forward Kinematics

Forward kinematics involves the use of known kinematic parameters of a robot’s joints and structure to compute the position and orientation of its end-effector. In the case of a shoulder exoskeleton based on a spherical wrist mechanism, forward kinematics utilizes the angles of each exoskeleton joint to determine the position and orientation of the end-effector which is effectively the user’s upper arm. However, only the orientation is considered during analysis since position does not affect singularity of the mechanism. Also, the position of the upper arm with respect to the shoulder is directly related to its orientation. Therefore, positional information can be omitted to simplify the problem during the analysis of the spherical wrist.

Forward kinematics of the 4R mechanism is achieved by the multiplication of the DH transformation matrices in (3.16) to (3.20):

\[ T_5^0 = T_1^0 T_2^1 T_3^2 T_4^3 T_5^4 \]  (3.21)

The resulting matrix represents the orientation of the coordinate system coupled to the upper arm with respect to the global coordinate system.

3.6 Inverse Kinematics

Inverse kinematics is the process of determining a set of required robot joint angles to reach a specified end-effector position. Solving the inverse kinematics problem is more challenging than the forward kinematics problem, particularly for a kinematically redundant system like the 4R mechanism.

There are infinite solutions to the inverse kinematics problem for any given end-effector position due to the kinematic redundancy of the 4R mechanism. However, if the desired end-effector position and the joint angle of one of the three proximal joints are known, the angles of the remaining joints can be derived using inverse kinematics. In this work, the angle of Joint 1 ($\theta_1$) is generated by an algorithm (this will be discussed in Chapter 4). Therefore, the inverse kinematics problem now involves finding the configuration of a non-redundant 3R mechanism (i.e. the angular positions $\theta_2$, $\theta_3$ and $\theta_4$) which has a finite number of solutions. However, $\theta_4$ only affects the axial rotation of the end-effector and not position since the end-effector is located in the same position as Joint 4. This means that the end-effector position (i.e. shoulder flexion & extension and abduction & adduction) is dependent on $\theta_1$, $\theta_2$ and $\theta_3$. 
while the end-effector axial orientation (i.e. shoulder medial & lateral rotation) is dependent on $\theta_4$. The resulting inverse kinematics problem is then to find $\theta_2$ and $\theta_3$ to achieve a desired end-effector position with a given value of $\theta_1$. Essentially, the positions of Joints 1, 2 and 4 are known and the position of Joint 3 needs to be found. The angular position of Joint 4, $\theta_4$, is considered separately and will be discussed later in Section 3.7.

3.6.1 FABRIK algorithm

The inverse kinematics problem for the 4R robot is solved using a heuristic iterative method based on the Forward and Backward Reaching Inverse Kinematics (FABRIK) algorithm [86]. The FABRIK algorithm has the advantage of converging to a solution with a relatively small number of iterations and has a low computational cost.

An iteration of the FABRIK method is a two stage process that begins at the last joint in the chain and works inwards, adjusting the position of each joint along the way. This process is then repeated outwards in the second stage to complete a full iteration. Each iteration moves the end-effector closer to the target position. Hence, the iterations are repeated until the end-effector is sufficiently close to the specified target position. A graphical representation of a full iteration of the FABRIK algorithm applied to a planar manipulator is presented in Figure 3.12.

Prior to applying the FABRIK algorithm, the target position is checked to determine whether it is reachable or not. For a planar manipulator, the end-effector can reach the target if the distance between the target and the base $d_{b\rightarrow t}$ is less than the total sum of all the link lengths $d_i$ for $n$ joints, i.e. the target is reachable if:

$$d_{b\rightarrow t} < \sum_{i=1}^{n-1} d_i \tag{3.22}$$

Assume $\mathbf{p}_1, ..., \mathbf{p}_n$ are the joint positions of a manipulator where $\mathbf{p}_1$ is the base joint and $\mathbf{p}_n$ is the end-effector. The target position for the end-effector is $\mathbf{t}$ and the initial base position is $\mathbf{b}$. The first stage of the algorithm starts at the end-effector, $\mathbf{p}_n$, and progresses inwards towards the manipulator base, $\mathbf{p}_1$. Firstly, the end-effector is moved to the target position, $\mathbf{p}_n' = \mathbf{t}$. The next step is then to find the new position of the joint before the end-effector, $\mathbf{p}_{n-1}'$. This is located on the line passing through the joint positions $\mathbf{p}_{n-1}$ and $\mathbf{p}_n'$, line $l_{n-1}$, at a distance of $d_{n-1}$ from $\mathbf{p}_n'$. Similarly, the new position of the joint $\mathbf{p}_{n-2}$, $\mathbf{p}_{n-2}'$, is located on the line passing $\mathbf{p}_{n-2}$ and $\mathbf{p}_{n-1}'$, line $l_{n-2}$, at a distance of $d_{n-2}$ from $\mathbf{p}_{n-1}'$. This continues until a new position for the base joint has been calculated (Figure 3.12).
Figure 3.12: An example of a full iteration of the FABRIK algorithm for a three-jointed planar manipulator [86]. (a) The initial position of the manipulator and the target, (b) move the end-effector \( p_4 \) to the target \( t \), (c) find the joint \( p_3' \) which lies on the line \( l_3 \) that passes through the points \( p_4' \) and \( p_3 \), and has distance \( d_3 \) from the joint \( p_4' \), (d) continue the algorithm for the rest of the joints, (e) the second stage of the algorithm begins by moving the base joint \( p_1' \) to its initial position, (f) repeat the same procedure but this time start from the base and backtrack outwards to the end-effector. The algorithm is repeated until the position of the end-effector gets sufficiently close to the target at the end of the second stage.
3.6 Inverse Kinematics

The second stage of the algorithm performs the same procedure as the first stage but starts at the base joint, \( p_1 \), and backtrack outwards to the end-effector instead. The new position of the base joint is assigned to the initial base position, \( p''_1 = b \). Then the new position of joint \( p'_{2}, p''_{2} \) is located on the line passing \( p'_{2} \) and \( p''_{1} \) at a distance of \( d_{1} \) from \( p''_{1} \). This is done until a new position for the end-effector is calculated which signifies the completion of a full iteration. Each iteration moves the end-effector closer to the target position. Therefore, the iterations are repeated until the end-effector is sufficiently close to the target position, \( t \).

3.6.2 Modified FABRIK algorithm

For manipulators that move in 3D space, the orientations of each revolute joint’s axis must also be considered when applying the FABRIK algorithm described above to ensure the constraints imposed by the links’ structures are enforced. This becomes a tedious task since both position and orientation must be considered. However, the characteristics of the 4R mechanism allow a simplified method to be used. For the 4R mechanism, which has all its joints rotate about an ICOR, inverse kinematics is effectively used to find the orientation of each joint axis with respect to the ICOR. The distances between the joints and the ICOR are constant and do not need to be considered. This allows angular positions to be used instead of linear positions which conveniently ensure the constraints of the 4R links are enforced. Therefore, the FABRIK algorithm has been modified for this research to utilize angular positions rather than linear positions.

Firstly, the conditions which cause a target end-effector position to be unreachable by the 4R mechanism are identified since there will not be an inverse kinematics solution. These conditions are less apparent with the 4R mechanism than with the 2D planar case in which the reachable range of the manipulator is determined simply by the sum of all link lengths. In the case of the 4R, the distance of the end-effector from the ICOR is always constant. Therefore, the unreachable angular directions of the end-effector are determined using the link angles. The end-effector of the 4R cannot reach a target position if any one of the following geometric conditions is true. These are when the angle at the ICOR between Joint 2 and the target end-effector position, \( \varphi_t \), is greater than the sum of the link angles \( \alpha_2 \) and \( \alpha_3 \) (3.23) or smaller than the difference between the link angles \( \alpha_2 \) and \( \alpha_3 \) (3.24). Examples of these two conditions are shown in Figures 3.13 and 3.14.

\[
\varphi_t > \alpha_2 + \alpha_3 \quad (3.23)
\]

\[
\varphi_t < |\alpha_2 - \alpha_3| \quad (3.24)
\]
These conditions apply to the problem specified at the beginning of this section, in which the positions of Joints 1 and 2 and target position of Joint 4 are known and the position of Joint 3 required to achieve the specified position of Joint 4 needs to be determined. In addition, distal joints are not permitted to be positioned under a proximal link. This is to ensure the links will not interfere with actuators attached on top of the joints.

Figure 3.13: Example of an unreachable target that satisfies (3.23).

Figure 3.14: Example of an unreachable target that satisfies (3.24).
The parameters in the modified FABRIK algorithm are defined similar to the definition used in the original FABRIK algorithm. \( \mathbf{p}_1, ..., \mathbf{p}_4 \) are the joint positions where \( \mathbf{p}_1 \) is Joint 1 and \( \mathbf{p}_4 \) is the end-effector (Joint 4), while \( \mathbf{t} \) is the target position for the end-effector and \( \mathbf{b} \) is the initial base position. Note that Joint 2 is the base joint in this problem since the angle of Joint 1 is predefined to ensure that a finite number of inverse kinematics solutions can be obtained.

The first stage of the algorithm requires each joint position to be adjusted from the end-effector to the base joint. Similar to the original algorithm, the end-effector is firstly moved to the target position, \( \mathbf{p'}_4 = \mathbf{t} \). The new position of Joint 3, \( \mathbf{p'}_3 \), is then found by rotating the position of the end-effector, \( \mathbf{p'}_4 \), about the ICOR by the angle of Link 3, \( \alpha_3 \), towards \( \mathbf{p}_3 \). Similarly, the new position of Joint 2, \( \mathbf{p'}_2 \), is located by rotating \( \mathbf{p'}_3 \) by the angle of Link 2, \( \alpha_2 \), towards \( \mathbf{p}_2 \).

The second stage adjusts the joint positions from the base joint (Joint 2) to the end-effector. The base joint is firstly moved to the initial base joint position, \( \mathbf{p''}_2 = \mathbf{b} \). The new position of \( \mathbf{p'}_3 \), \( \mathbf{p''}_3 \), is then found by rotating the position of the base joint, \( \mathbf{p''}_2 \), by the angle of Link 2, \( \alpha_2 \), towards \( \mathbf{p}_3 \). This is repeated for Link 3 to find a new position for the end-effector. This completes a single iteration of the modified FABRIK algorithm. The iterations are repeated until the end-effector position is sufficiently close to the target position, \( \mathbf{t} \).

### 3.6.3 Implementation of the modified FABRIK algorithm

*Transforming the target position into the coordinate system of the base joint (Joint 2)*

The target end-effector position is initially defined in the global coordinate system. This needs to be transformed into the coordinate system of the base joint, Joint 2, before solving the inverse kinematics problem. Using the given value of \( \theta_1 \), the target position is transformed from the global coordinate system into the coordinate system of Joint 2 using (3.25) where \( T^0_2 = T^0_1 T^1_2 \), \( c_0 \) is the coordinates of the target position in the global coordinate system and \( c_2 \) is the coordinates of the target position in the coordinate system of Joint 2.

\[
c_2 = T^0_2 c_0
\]  

(3.25)

*Rotating positions*

The modified FABRIK algorithm requires the rotation of joint positions about the origin. This is done using Quaternion rotations. Quaternions are a convenient mathematical notation for representing orientations and rotations of objects in 3D space. Euler’s rotation theorem
states that any rotation or sequence of rotations about a fixed point is equivalent to a single rotation by a given angle about a fixed axis that runs through the fixed point called the Euler axis. The Euler axis is represented by a vector in the Cartesian coordinate system and the angle of rotation is represented by a scalar. A Quaternion is defined by four parameters (3.26) where the three parameters $x$, $y$ and $z$ describe the axis of rotation and the fourth parameter $w$ indicate the angle of rotation about this axis [87].

$$q(w, x, y, z)$$ (3.26)

Rotation quaternions can be used to rotate a point in 3D space about a specified axis by a specified angle. Since only a single rotation is performed, this method does not have the singularity problem that occurs when using a sequence of Euler rotations.

The rotational transformation matrix corresponding to the quaternion rotation is obtained from:

$$Q = \begin{bmatrix} w^2 + x^2 - y^2 - z^2 & 2xy - 2wz & 2xz + 2wy \\ 2xy + 2wz & w^2 - x^2 + y^2 - z^2 & 2yz - 2wx \\ 2xz - 2wy & 2yz + 2wx & w^2 - x^2 - y^2 + z^2 \end{bmatrix}$$ (3.27)

For a unit Quaternion, this can be simplified to:

$$Q = \begin{bmatrix} 1 - 2y^2 - 2z^2 & 2xy - 2wz & 2xz + 2wy \\ 2xy + 2wz & 1 - 2x^2 - 2z^2 & 2yz - 2wx \\ 2xz - 2wy & 2yz + 2wx & 1 - 2x^2 - 2y^2 \end{bmatrix}$$ (3.28)

This transformation matrix is applied to the joint position to rotate it about the axis defined by $x$, $y$, and $z$ with an angle of $w$ to find the position of the adjacent joint:

$$p_{n-1} = Q p_n$$ (3.29)

Using the first step of the modified FABRIK algorithm as an example: the axis of rotation defined by $x$, $y$, and $z$ is orthogonal to the plane formed between $p'_4$, $p_3$ and the ICOR. The angle of rotation $w$ is the angle size of Link 3, $\alpha_3$. Applying the Quaternion rotation transforms the new position of the end-effector, $p'_4$, into the coordinates of the new position of Joint 3, $p'_3$.

Starting joint configuration

The modified FABRIK algorithm always requires a starting configuration to converge from. However, there are configurations that can cause the algorithm to fail in converging to a solution. This occurs when the second stage of the algorithm returns the joint configuration to the state prior to the first stage. The starting configurations that cause this have all three
3.7 Range of Motion of Joint 4 and Shoulder Axial Rotation

joints positioned in the same plane (i.e. when Links 2 and 3 are parallel with each other). Therefore, to avoid this problem, a starting configuration is generated which has Link 3 positioned orthogonal to Link 2. However, if the inverse kinematics solution to achieve a target end-effector position requires all three joints to be positioned near the same plane (i.e. requires Link 2 to be parallel with Link 3), the algorithm converges very slowly and requires many iterations. To avoid this, the algorithm first checks if the angle between the target end-effector position and the base joint (Joint 2) position about the ICOR is equal to either the sum or the difference of the two link angles. If this is the case, then the inverse kinematics solution is simply a configuration with the two links pointing towards the target end-effector position and the modified FABRIK algorithm does not need to be applied.

Conditions for terminating the algorithm

In this research, the modified FABRIK algorithm is terminated once a configuration is obtained with an end-effector position error of less than 1°. This configuration is selected as the solution to the inverse kinematics problem. In addition, the algorithm is terminated if the error threshold is not achieved after 2,000 iterations as a precaution to prevent infinite loops.

Symmetrical inverse kinematics solutions

It has been realized that there are two possible inverse kinematics solutions in most cases, even when the position of Joint 2 is given. An example of this is shown in Figure 3.15. The two possible solutions are mirror images of each other with the plane of symmetry intersecting the axis of Joint 2 and the end-effector position. The only case in which there is only one inverse kinematics solution is when Joint 3 also lies in this plane of symmetry. Both inverse kinematics solutions are considered by the optimization algorithm outlined in Chapter 4.

3.7 Range of Motion of Joint 4 and Shoulder Axial Rotation

Joint 4 in the 4R mechanism is implemented using a curved rail mechanism around the upper arm. It is important to keep the range of motion of Joint 4 small to minimize the size of the rail used for this joint. A smaller rail makes the device easier for the user to don and reduces the invasiveness of the mechanism. As discussed in Section 3.6, Joint 4 can independently control shoulder axial rotation. Therefore, the range of motion of this joint needs to match that of shoulder axial rotation. The design of this joint is presented in Section 5.2.7.
Figure 3.15: Example of two inverse kinematics solutions in which the 4R mechanism has the same Joint 1, 2 and 4 (end-effector) positions but different Joint 3 position. These two solutions are mirror images of each another with the plane of symmetry intersecting the axis of Joint 2 and the end-effector.

However, the range of motion of both Joint 4 and the human shoulder axial rotation drifts depending on the end-effector (or upper arm) position in the workspace [88]. In the case of Joint 4, this drift depends on the kinematic design of the 4R spherical wrist mechanism. Therefore it is necessary to compare the angular position drift of the exoskeleton’s Joint 4 with the corresponding drift of the shoulder’s axial rotation. A deviation between the two drifting angular positions will require Joint 4 to have a larger range of motion to ensure the exoskeleton can reach the extreme limits of shoulder axial rotation. The maximum deviation between the two drifting angular positions in both the positive and negative rotational direction determine the additional range of motion required in Joint 4.

3.8 Chapter Summary

Analysis of the 3R spherical wrist mechanism for a shoulder exoskeleton has revealed its major flaws. Due to the large range of motion of the human shoulder, the 3R mechanism is unable to avoid operating near a singular configuration where it loses 1 DOF. When operating near the singular configuration, a small rotation of the shoulder about the affected axis requires high velocities from the 3R joints. This is difficult to achieve in control and such fast movements are more likely to cause injuries or discomfort for the user.
Furthermore, the links of the 3R mechanism are required to operate dangerously close to the user’s body in order to reach some regions of the shoulder workspace.

This chapter proposes a kinematically redundant 4R spherical wrist to overcome the limitations of the 3R. It is realized that singular configurations of the spherical wrist mechanism is independent of the distance between the joint and the ICOR and only dependent on the joints’ orientations. Therefore, modeling of the 4R mechanism is simplified by only considering orientations and ignoring distances. The kinematics of the 4R mechanism is modeled using the DH notation and methods to solve the forward kinematics and inverse kinematics problems are developed.

Due to the redundancy of the 4R mechanism, a range of designs are possible which can achieve the desired performance for a shoulder exoskeleton. In addition, a given 4R end-effector position has infinite inverse kinematics solutions because of the kinematic redundancy of the mechanism. To obtain an inverse kinematics solution, it is proposed that a value is set for the angular position of Joint 1 in the 4R mechanism so that the remaining joints form a non-redundant 3R mechanism. A modified FABRIK algorithm is proposed and developed to solve the inverse kinematics problem of the 4R mechanism.

The models and methods presented in this chapter provide the groundwork for finding an optimal 4R design through the use of an optimization algorithm.
4

Design Optimization of a 4R Shoulder Mechanism

The major limitations of using a 3R spherical wrist mechanism for a shoulder exoskeleton have been identified in Chapter 3. The use of a redundant 4R spherical wrist is proposed to overcome the singularity and mechanical interference problems of the 3R mechanism and enable the exoskeleton to achieve the full spherical workspace of a healthy human shoulder with good performance. However, due to its kinematic redundancy, there are a range of 4R mechanism designs that can achieve the desired performance in a shoulder exoskeleton. In particular, the sizes of the link angles and the position of the 4R base joint can be adjusted to a certain degree without preventing the exoskeleton from achieving the full shoulder workspace. Furthermore, the redundant 4R mechanism has infinite inverse kinematics solutions. Since there are a variety of options, it is possible to find an optimal 4R design with high performance and also the optimal joint configurations for this design to operate with.

This chapter discusses the optimization of the 4R mechanism specifically for a shoulder exoskeleton. The concepts behind multi-objective optimization and the NSGA II algorithm are presented. The optimization problem is outlined, discussed and a set of optimization variables and objectives are defined for the NSGA II algorithm. The workspace of the human shoulder is considered and factors that can limit the workspace of the 4R mechanism are
analyzed. Algorithms are developed to evaluate the performance of a given 4R design in terms of joint velocities during transitions of the end-effector and proximity to singular configurations. The outcome of the optimization is an optimal kinematic design of the 4R mechanism and a set of optimal joint configurations for this redundant mechanism to operate with. This optimal 4R design is analyzed and its performance discussed with comparisons to other shoulder exoskeleton designs.

4.1 Optimization Algorithms

Classic single objective optimization involves finding a single solution that best meets the objective, typically solved by using derivatives to find a maxima or minima. However, when there are multiple conflicting objectives involved in the optimization problem, a single solution does not necessarily exist that can optimize each objective simultaneously. In multi-objective optimization problems, a range of quality solutions can be obtained with each solution consisting of trade-offs between the objectives. These solutions are referred to as Pareto optimal or non-dominated and are defined as solutions with objective values that cannot be improved upon without degrading at least one other objective value [89]. The set of Pareto optimal solutions is called the Pareto set and the representation of the Pareto set in the objective space is the Pareto front. Figure 4.1 shows a typical Pareto front for a two-objective optimization problem.

![Pareto front](image)

**Figure 4.1:** Pareto front of solutions for a two-objective optimization problem.

In mathematical terms, a multi-objective optimization problem can be formulated as (4.1) where the integer $k \geq 2$ is the number of objectives and the set $X$ is the feasible set of decision vectors [90]:
4.1 Optimization Algorithms

\[
\begin{align*}
\text{minimise} & \quad F(x) = (f_1(x), \ldots, f_k(x)) \\
\text{s. t.} & \quad x \in X,
\end{align*}
\] (4.1)

A feasible solution \( x_1 \) is said to Pareto dominate another solution \( x_2 \) if:

\[
\begin{align*}
& f_i(x_1) \leq f_i(x_2) \quad \text{for all indices } i \in \{1, \ldots, k\} \quad (4.2) \\
& f_j(x_1) < f_j(x_2) \quad \text{for at least one index } j \in \{1, \ldots, k\} \quad (4.3)
\end{align*}
\]

Solving a multi-objective optimization problem involves simultaneously finding all Pareto optimal solutions for the set of objective functions [89]. However, all Pareto optimal solutions are considered equally good therefore a human decision maker is required to make a subjective selection of a single Pareto optimal solution. This decision maker is expected to be an expert in the problem. Methods used to solve single objective optimization problems are not suitable for multi-objective optimization problems in which multiple solutions are to be found.

Methods used to solve multi-objective optimization problems can be categorized into four classes [91]. These are the no preference, a priori, a posteriori and interactive methods. Among the four methods, the no preference method is the only method with no human decision maker involved. In this method, a neutral compromise solution is identified without preference information. A priori methods require preference information from the decision maker before a solution that best satisfies the preferences is found. A posteriori methods find a set of Pareto optimal solutions which the decision maker can then select one solution from. Interactive methods allow the decision maker to search for the most preferred solutions after each iteration of the algorithm. These preferred solutions are then used to generate the next generation of solutions.

Among these, an algorithm using the a posteriori method is most suitable for optimizing the 4\(R\) mechanism in this research. The no preference method is not suitable as there will certainly be user preferences when selecting a Pareto optimal solution. In the case of the a priori method, it is difficult to specify all the preference information due to the high complexity of the multi-objective optimization problem. The complexity of the problem also makes it difficult for a decision maker to identify preferable solutions for the interactive method.

Evolutionary algorithms have emerged as popular a posteriori methods for generating a set of Pareto optimal solutions for multi-objective optimization problems [89]. Their main advantage is the fact that they work with a population of solutions and therefore can
4.1 Optimization Algorithms

Optimization algorithms approximate the entire Pareto set in a single simulation run [92]. They also do not require derivatives of objective functions and use robust operators to avoid convergence to local optima. Evolutionary algorithms’ main disadvantage is their lower speed which is not an issue in this research. Numerous multi-objective evolutionary algorithms have been proposed by researchers in the past two decades to solve multi-objective optimization problems [89, 93-95]. There have been many successful applications of evolutionary algorithms in a range of real-world problems such as in engineering design, groundwater monitoring, autonomous vehicle navigation and city planning [96].

Optimization algorithms have been used in several exoskeleton robots in the recent past. Examples include optimization of hand exoskeletons [97, 98], lower limb exoskeletons [99, 100] and shoulder exoskeletons [101, 102]. In the case of shoulder exoskeletons, Klein et al. optimized the design of a parallel mechanism [101] while Agrawal et al. optimized the design of a cable driven mechanism with motors mounted on a shoulder cuff [102]. Although workspace is considered in the optimization of both mechanisms, the type of mechanism used prevented the exoskeleton from achieving the entire reachable workspace of the human shoulder. The 4R mechanism proposed in this research aims to overcome this limitation and allow a shoulder exoskeleton to achieve the entire spherical shoulder workspace.

4.1.1 The NSGA II algorithm

A popular multi-objective evolutionary algorithm used by researchers is the Non-dominated Sorting Genetic Algorithm II (NSGA II) [92]. NSGA II has been shown to perform better than other well-known multi-objective evolutionary algorithms including the Pareto-archived evolution strategy (PAES) [95] and strength Pareto evolutionary algorithm (SPEA) [94] in terms of finding a diverse set of solutions and in converging near the true Pareto optimal set. Therefore, NSGA II is chosen as the multi-objective evolutionary algorithm for optimizing the design of the 4R mechanism in this research.

NSGA II is based on genetic algorithm, a popular evolutionary algorithm which uses techniques inspired by the process of natural evolution. An initial population of solutions (or chromosomes) is randomly generated and three natural operators, namely selection, crossover and mutation, are applied to generate a new population of better solutions. This process is repeated iteratively to obtain better and better solutions until a termination condition is reached. A common termination condition is setting a maximum number of iterations to be performed.
The selection operator uses a fitness function to determine the quality of the solutions. The fitness is often determined using the objective functions of the optimization problem being solved. Solutions with high fitness are selected to become parents in the breeding of new offspring solutions for the next generation. The crossover operator is responsible for creating new offspring solutions by combining two or more high fitness parent solutions selected by the selection operator. Offspring solutions obtained this way shares many of the characteristics of its parents. Since only the best solutions were selected for breeding, the new generation of solutions will often have a higher average fitness. Finally, the mutation operator ensures the diversity of solutions is maintained by randomly changing some solutions for the next generation. Mutation allows the algorithm to avoid local optima by preventing the population of solutions from becoming too similar to each other which can slow or stop evolution. The level of mutation is based on a user-defined mutation probability which is kept low to ensure the solutions will converge towards the Pareto optimal set. The evolution mechanism in NSGA II enables exploration of various trade-off solutions which allows an approximation of the Pareto set to be found and preserves the diversity of solutions. These are two key features of multi-objective evolutionary algorithms.

The NSGA II algorithm is illustrated in Figure 4.2 and has the following steps:

1. [Start] Select a termination criterion based on number of iterations.
2. [Initialize] Initialize a random population of Q chromosomes (suitable solutions).
3. [Fitness] Evaluate the values of various objectives for each chromosome in the population.
4. [Rank] Classify population into fronts using non-dominating sorting algorithm and assign non-domination ranks to each solution.
5. [Offspring] For the first iteration, create a duplicate copy of the parent population by randomly arranging its solutions and call this offspring population.
6. [Selection] Combine offspring with the parent population and select Q solutions based on non-domination rank. Call the resulting population as parents.
7. [Crossover] Crossover the parents with a crossover probability to form new offspring.
8. [Mutation] Mutate the new offspring with a chosen mutation probability.
9. [Rank] Evaluate solutions for their objective values to perform non-dominated sorting and once again classify the population into fronts based on their non-domination ranks.
10. [Check] Check for the termination criteria and stop if this is achieved else go to Step 6.
11. [End] Stop and return the final population when the termination criterion is reached.
4.2 The Optimization Problem

As discussed in Chapter 3, a kinematically redundant 4R mechanism can avoid the undesirable singular configurations that can occur with a 3R mechanism and achieve good performance in the entire shoulder workspace. The goal is to optimize the 4R mechanism to ensure the additional DOF provided by the redundant joint is efficiently utilized to achieve a high performance in a shoulder exoskeleton. This involves finding an optimal 4R design and also a set of optimal joint configurations for the mechanism [103].

The redundant joint in the 4R mechanism allows flexibility in the 4R linkage design. Whereas a 3R mechanism requires all link angles to be 90° in order to achieve the full spherical workspace, the link angles of the redundant 4R mechanism can have a variety of sizes and still achieve the full spherical workspace. Hence, there are a range of possible 4R mechanism designs that can be used in a shoulder exoskeleton. The 4R design can have variations in the sizes of the three link angles and the location of the base joint as shown in Figure 4.3.
4.2 The Optimization Problem

In addition, an issue arising from the redundancy is that it is possible to achieve the same end-effector position with a range of different 4R configurations as shown in Figure 4.4, i.e. there are infinite inverse kinematics solutions. Therefore, it is also necessary to identify the optimal joint configuration for reaching any given end-effector position in the shoulder workspace. The NSGA II algorithm is used to solve this complex non-linear optimization problem.

Figure 4.3: Example of two different 4R designs with different link angle sizes and base joint position.

Figure 4.4: Example of two different joint configurations of the same 4R design which both achieve the same end-effector position.
4.2 The Optimization Problem

4.2.1 Variables

Six variables are used in this optimization problem. Descriptions for these variables and their permitted values are shown in Table 4.1. The first five variables describe the design of the 4R mechanism, where $\alpha_1$, $\alpha_2$ and $\alpha_3$ describe the three link angles and $\varphi_z$ and $\varphi_x$ describe the position of the base joint relative to the user’s shoulder in spherical coordinates. Here, $\varphi_z$ precedes $\varphi_x$ in the sequence of Euler rotations and the default position is directly above the user’s right shoulder. The sixth variable $\theta_1^0$ is used to determine the optimal joint configurations of the 4R mechanism. This variable is the angle of Joint 1 ($\theta_1$) when the end-effector is at the center of the shoulder workspace. These three latter variables are illustrated in Figure 4.5. A given value of $\theta_1$ is necessary because there are infinite possible joint configurations for achieving a given end-effector position due to the kinematic redundancy. If $\theta_1$ is known, the angular positions of the remaining joints required to achieve the given end-effector position can be determined from inverse kinematics. However, this only gives the configuration for reaching one position in the workspace. Therefore, an expanding algorithm is developed to compute the joint configurations for reaching the remaining workspace. Further details on this expanding algorithm are provided in Section 4.3.3.

The three links $\alpha_1$, $\alpha_2$ and $\alpha_3$ in the 4R mechanism are constrained to an angle size of between 20° and 160° as shown in Table 4.1. A link angle size of less than 20° is too small to implement as a link and a link greater than 160° introduces a large obstruction into the workspace. It is expected that the optimal 4R link angles will be similar or smaller than the 90° links of the 3R. The permitted ranges of $\varphi_z$ and $\varphi_x$ are selected to ensure the stationary Joint 1 can only be positioned in the region behind the user’s shoulder. This prevents mechanical interference between Joint 1 and the user since this region is outside the reachable workspace of the user’s arm. The variable $\theta_1^0$ representing the angular position of Joint 1 at the workspace center is allowed to have a value in the entire 360° range. These six variables are illustrated in Figure 3.11 and Figure 4.5.

The NSGA II algorithm produces a population of solutions, each with a value for the six variables within their permitted ranges. Each iteration of the algorithm improves these solutions until a set of Pareto optimal solutions are obtained.

4.2.2 Objectives

In this optimization problem, achieving the entire human shoulder workspace without mechanical interference is considered to be a compulsory objective. The other performance objectives are average joint motion, global condition number and maximum condition...
4.2 The Optimization Problem

number. The NSGA II algorithm uses these three performance objectives to evaluate each solution that can reach the entire shoulder workspace and the best performing solutions are selected for producing the next generation of solutions. These objectives are discussed in the subsequent sections.

Table 4.1: Optimization variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Permitted Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_1$</td>
<td>Angle size of Link 1</td>
<td>20° to 160°</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>Angle size of Link 2</td>
<td>20° to 160°</td>
</tr>
<tr>
<td>$\alpha_3$</td>
<td>Angle size of Link 3</td>
<td>20° to 160°</td>
</tr>
<tr>
<td>$\varphi_z$</td>
<td>Spherical coordinate of Joint 1 location about z-axis</td>
<td>-45° to 45°</td>
</tr>
<tr>
<td>$\varphi_x$</td>
<td>Spherical coordinate of Joint 1 location about x-axis</td>
<td>-90° to 90°</td>
</tr>
<tr>
<td>$\theta_1^0$</td>
<td>Joint 1 angle when the end-effector is at the workspace center</td>
<td>-180° to 180°</td>
</tr>
</tbody>
</table>

Figure 4.5: Illustration of the optimization variables $\varphi_z$, $\varphi_x$, and $\theta_1^0$. 
4.3 Workspace of the 4R Mechanism

The 4R mechanism is intended for a shoulder exoskeleton therefore the workspace of the human shoulder needs to be considered during optimization. The workspace for the human shoulder is approximately half of the spherical workspace (i.e. a semi-sphere) while the 4R exoskeleton can be designed to operate the end-effector in the entire spherical workspace. Such a large workspace is not necessary for a shoulder exoskeleton since the workspace of the human shoulder is significantly smaller. Compromises can be made in the 4R design to sacrifice performance in the workspace which the human shoulder cannot reach to improve performance in the workspace which the shoulder can reach. Hence, the 4R design is optimized for only the shoulder workspace rather than the entire spherical workspace. However, it is difficult to analyze the mechanism’s performance for the entire continuous workspace. Therefore, performance is assessed for a pre-defined set of end-effector positions in the shoulder workspace. In this research, the shoulder workspace is represented by a semi-sphere. Since the shoulder workspace of an average person is slightly smaller than a semi-sphere, this guarantees the entire workspace of an average shoulder is covered.

4.3.1 Discretized workspace

The semi-spherical shoulder workspace is discretized into points, each indicating an end-effector position to be analyzed. A common method for allocating points on the surface of a sphere is by using the longitude and latitude parameters. However, this method results in a non-uniform distribution of points with a higher density of points at the two poles of the sphere. This causes the performance near the poles to have a larger influence on the overall performance score. Ideally the points should be uniformly distributed to ensure the workspace is analyzed evenly. A set of 89 uniformly distributed points over the semi-spherical workspace is generated using an algorithm proposed by N.A. Teanby [104]. This algorithm performs repeated subdivisions of a spherical icosahedron to obtain an increasingly dense grid of evenly distributed points on the surface of a sphere. Figure 4.6 shows the spheres from two consecutive subdivisions.

The number of uniformly distributed points \( N \) that can be obtained using this algorithm is calculated using (4.4) where \( k \) is a positive integer.

\[
N = 2 + (10 \times 4^k) \quad (4.4)
\]

The four lowest number of spherical points that can be obtained from this method are 12, 42, 162 and 642 points. Figure 4.7 shows the semi-spheres for the three latter cases.
4.3 Workspace of the 4R Mechanism

Figure 4.6: Illustration of two consecutive subdivisions of a spherical icosahedron [104]. The black dots represent evenly distributed points on the surface of a sphere.

Figure 4.7: Uniformly distributed semi-sphere points obtained from the spheres with 42, 162 and 642 points.
4.3 Workspace of the 4R Mechanism

A sphere of 162 points is selected for representing the end-effector positions as this has a sufficient point density to provide a good representation of the 4R performance over the workspace. Since only the shoulder workspace is required rather than the entire spherical workspace, only 89 of the 162 points are used. These points cover a semi-spherical region in the lateral-anterior region of the user’s shoulder as shown in Figure 4.8.

4R joint configurations are assessed for each of the 89 end-effector positions. The optimal joint configurations to reach each of the 89 end-effector positions are determined using the expanding algorithm in Section 4.3.3. Interpolation can then be used to find the joint configuration to reach any arbitrary end-effector position in the shoulder workspace.

4.3.2 Workspace limitations

As mentioned in Section 4.2.2, achieving the entire shoulder workspace is a compulsory objective for the 4R mechanism. This is formulated as a piecewise function (4.5) which gives a poor (large) value for the optimization algorithm if at least one of the 89 workspace positions is unreachable. The objective is to minimize $f_{ws}$.

$$f_{ws} = \begin{cases} 1 & \text{if all 89 positions can be reached} \\ 10000 & \text{if 1 or more of the 89 positions cannot be reached} \end{cases} \quad (4.5)$$

Figure 4.8: The semi-spherical shoulder workspace is discretized into 89 uniformly distributed points for analysis. The model user shown has a shoulder posture at the center of the workspace, represented by a red point.
The workspace of the 4R mechanism is limited by three factors. If any of these three cases occur with all possible joint configurations for an end-effector position, the end-effector position is considered unreachable. The first case occurs when there is no inverse kinematics solution for the given end-effector position and Joint 1 angle. This occurs when the end-effector cannot reach the position with the given link dimensions. The method used to identify this situation is explained in Section 3.6.2. The second case occurs when the joint configuration is at or very close to a singular configuration. Since there are significant limitations in operating at a singular configuration, the end-effector position that causes the singular configuration cannot be included into the robot operating workspace. The methods used to analyze singularities are discussed in Section 4.4.

The final case occurs when a part of the 4R structure is required to enter a forbidden region to reach an end-effector position. These include regions that can harm or cause discomfort for the user or cause mechanical interference between different parts of the exoskeleton system. The robot can harm the user if the mechanism links collide with a part of the user’s body. With the design concept used, the mechanism links can potentially collide with the user’s torso, neck or head when moving towards a certain end-effector position. Collision with the upper arm due to link movements is not possible since the 4R end-effector moves with the upper arm. Therefore, the links must not enter the user’s medial region with respect to the ICOR. Furthermore, operating the links in the user’s field of view can cause unease and intimidate the user. Therefore, the links must also not enter the user’s anterior region. End-effector positions that require the links to enter the user’s medial or anterior regions are considered unreachable. The boundary for this region is specified by a vertical plane intersecting the ICOR with a normal axis in the anterior-medial direction, 45° from the anterior axis. In addition, the region near the head and torso are also forbidden, i.e. the region above and below the ICOR. This region is represented by a vertical cylindrical volume with an axis intersecting the ICOR. Figure 4.9 shows the boundary of the region which the 4R mechanism must not enter.

Detecting the 4R in forbidden region

To identify whether the 4R mechanism enters the forbidden region, the locations of Joints 1, 2 and 3 are checked. Joint 4 is at the end-effector which is always located within the upper arm workspace due to the design, therefore this joint will not cause any forbidden intrusions. To ensure the 4R mechanism does not enter the medial-anterior region of the user, the
condition in (4.6) must be met where $x_j$ and $y_j$ are respectively the x and y Cartesian coordinates of the location of joint $j$ in the global coordinate system.

$$x_j > y_j \quad for \ j = 1, 2, 3$$

(4.6)
Furthermore, the intrusion into the region above and below the shoulder ICOR is also forbidden and (4.7) must also be satisfied, where \( d \) is the minimum allowable distance between a 4R joint and the vertical axis intersecting the shoulder ICOR.

\[
\sqrt{x_j^2 + y_j^2} > d \quad \text{for } j = 1, 2, 3
\]  

(4.7)

If a joint location does not satisfy both of the conditions (4.6) and (4.7) then it has entered the forbidden region and the joint configuration is considered unable to reach the end-effector position.

The coordinates of Joint 1, 2 and 3 with respect to the global coordinate system are derived using the DH transformation matrices of the 4R mechanism. Given that the coordinate systems are defined according to the DH notation and that the axes of rotation of all the joints intersect with the origin of the global coordinate system, the z-axis of the local coordinate system at each joint indicates the direction the joint is located with respect to the global coordinate system. The normalized coordinates of the jth joint’s local z-axis with respect to the global coordinate system can be obtained from (4.8) where \( a_x \), \( a_y \), and \( a_z \) are obtained from the DH matrix (4.9). (4.6) and (4.7) are then used to check whether any joint lies in the forbidden region.

\[
(x, y, z)_j = (a_x, a_y, a_z)_j^0
\]  

(4.8)

\[
T_j^0 = \begin{bmatrix}
    n_x & o_x & a_x & r_x \\
    n_y & o_y & a_y & r_y \\
    n_z & o_z & a_z & r_z \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]  

(4.9)

In addition, Joint 1 must not be positioned within the shoulder workspace. This is because the position of Joint 1 is fixed and positioning this joint inside the shoulder workspace will prevent the upper arm from entering this region of the workspace. Therefore, the location of Joint 1 is restricted to a region behind the shoulder joint. This is reflected in the permitted ranges of \( \varphi_z \) and \( \varphi_x \) shown in Table 4.1.

4.3.3 Optimization for the entire workspace

The inverse kinematics discussed in Section 3.6 only computes the joint configuration for one end-effector position in the shoulder workspace. It is not feasible to compute the optimal joint configuration for the entire continuous workspace therefore only the optimal joint configurations for the 89 workspace positions will be identified. However, if an optimal joint
configuration is found for each end-effector position independently, then the end-effector positions that are adjacent to one another may have very different joint configurations and therefore require large joint displacements to move between. Ideally, the optimal joint configuration identified for every end-effector position will be able to transition to an adjacent position smoothly with minimal joint displacements. This is part of the first performance objective defined in the optimization problem, the average joint motion.

An expanding algorithm has been developed to obtain the optimal joint configurations for all 89 end-effector positions in the shoulder workspace while ensuring feasible joint transitions. This makes use of the value $\theta_1^0$ which is generated by the NSGA II algorithm as the sixth variable. This variable is the $\theta_1$ value for reaching the end-effector position at the center of the shoulder workspace. The expanding algorithm firstly finds the optimal joint configuration for this center position using the six variable values of the solution provided by the NSGA II algorithm. The algorithm then computes the optimal joint configurations for all the end-effector positions adjacent to this starting position. This is done while ensuring the transition between adjacent end-effector positions are realistic, requires minimal joint displacements, does not cause interference and avoids approaching a singular configuration. This is achieved by generating a range of $\theta_1$ values for the adjacent child position which are within $20^\circ$ of the parent positions’ $\theta_1$ value and analysing the performance of their respective joint configurations. The $\theta_1$ value that gives the best performing joint configuration is then selected as the optimal for the child end-effector position. This is done for each end-effector position that is adjacent to the parent position and has not already been analyzed. The process is then applied to the next layer of adjacent end-effector positions and is repeated until all 89 positions in the shoulder workspace have been investigated. Figure 4.10 shows the first two iterations of the expanding algorithm.

By starting from the center end-effector position in the workspace, the expanding algorithm is completed with the minimum number of iterations. The overall ease of transition between every combination of adjacent end-effector positions is used as part of the average joint motion objective in the optimization algorithm. This is calculated as the average change in joint angles between the joint configurations of every pair of adjacent end-effector positions $\Delta \theta_{avg}$. The objective is to minimize (4.10) where $\Delta \theta(i,j,k)$ is the change in joint angle of joint $i$ in moving the end-effector from workspace position $j$ to an adjacent position $k$, $m$ is the number of end-effector positions adjacent to position $j$, $n$ is the total number of workspace positions.
Figure 4.10: The first two iterations in the expanding algorithm. Each iteration finds the joint configurations for a new layer of end-effector positions. The red points represent the positions to be analyzed in the current iteration and the blue points represent the positions that have already been analyzed in a previous iteration.
The resulting set of 89 \( \theta_1 \) values which achieves optimal joint configurations for reaching the 89 end-effector positions will be used to control the kinematically redundant robot. Interpolation of the 89 \( \theta_1 \) values can be done to find the optimal joint configuration for any arbitrary end-effector position in the shoulder workspace. This is achieved by interpolating the set of \( \theta_1 \) data to find the optimal \( \theta_1 \) value followed by inverse kinematics to compute the corresponding \( \theta_2 \) and \( \theta_3 \) values. The joint angles obtained represent the optimal joint configuration for reaching the specified end-effector position.

### 4.3.4 Minimizing the required range of motion of Joint 4

Joint 4 in the 4R mechanism can independently adjust shoulder axial rotation due to its kinematic structure. This joint is implemented using an arc-shaped rail mechanism around the upper arm and has an arc size that depends on the range of motion requirement of the joint. A small range of motion requirement of Joint 4 is preferable as this means a smaller sized rail can be used which makes the exoskeleton easier to don and also reduces the amount of interference with the user. Note that the 3R exoskeleton requires a large circular rail in order to achieve full range of motion of shoulder axial rotation over the workspace due to the mismatch between the joint and the upper arm at different workspace positions. This causes three major issues. Firstly, a circular rail makes the exoskeleton difficult to don. Secondly, the circular rail interferes with the user’s torso when the arm is lowered. Lastly, in order to mitigate the second problem the circular rail must have a thin design. Designing a thin circular rail is a challenging task and such a design can compromise the performance of the joint. Thus, minimizing the size of the Joint 4 rail is important in achieving a user-friendly exoskeleton.

Due to the kinematics of the 4R spherical wrist mechanism, the angular position of Joint 4 relative to the global coordinate system drifts as the mechanism configuration changes. This drift is dependent on the kinematic design of the 4R mechanism. In addition, the range of motion of shoulder axial rotation also changes depending on the position of the upper arm. Experiments done by Wang et al. [88] shows that as the shoulder is horizontally flexed, the limit of medial rotation decreases while the limit of lateral rotation increases. A deviation between the two drifting angular positions will require Joint 4 to have a larger range of motion to ensure the exoskeleton can reach the extreme limits of shoulder axial rotation.
Therefore, to minimize the range of motion requirement of Joint 4, its drifting angular position needs to be kept close to the drift of shoulder axial rotation for the entire shoulder workspace.

In this research work, the range of motion of shoulder axial rotation is assumed to drift linearly up to 45° between the limits of horizontal flexion and extension. It is desirable to minimize the largest clockwise and counter-clockwise angular offset between the angular position of Joint 4 and the angular position of shoulder axial rotation that occurs in the workspace. A small maximum offset will mean that only a small additional range of motion is required for Joint 4 on top of the range of motion of shoulder axial rotation. This is included as part of the average joint motion objective in the optimization problem.

The objective is to minimize (4.11) where $\Delta \theta^4_{\text{max}}$ is the additional range of motion required for Joint 4, $\theta^4_0(j)$ is the default angular position of Joint 4 at end-effector position $j$ relative to the global coordinate system, and $\theta^\sigma_0(j)$ is the default angular position of shoulder axial rotation at upper arm position $j$ relative to the global coordinate system.

$$\Delta \theta^4_{\text{max}} = \max(\theta^4_0(j) - \theta^\sigma_0(j)) - \min(\theta^4_0(j) - \theta^\sigma_0(j)) \quad \text{for } j = 1, \ldots, n$$  \hspace{1cm} (4.11)

\textbf{4.4 Singularity Analysis}

As discussed in Chapter 3, it is desirable to have the 4R mechanism operate far away from singular configurations in order to reduce joint velocities. At a singular configuration, the end-effector loses the ability to move in a particular direction and therefore it is also impossible to exert force in that direction.

Singularity analysis is done using Jacobian matrices and its condition number which has often been used as measures of robot manipulability [100, 105, 106]. The Jacobian matrix of the robot maps the robot’s joint velocities to the angular velocity of the end-effector according to (4.12) where $\omega$ is the angular velocity of the end-effector, $J$ is the Jacobian matrix and $\dot{\theta}$ is the joint velocity vector.

$$\omega = J \dot{\theta}$$  \hspace{1cm} (4.12)

The condition number of this Jacobian matrix $k(J)$ has a useful physical property as shown by (4.13) where $F$ is the force exerted at the end-effector, $\tau$ is the joint torque, and $\delta F$ and $\delta \tau$ are the force error and torque error respectively [105].
This shows that the condition number can map the torques generated by the robot’s joints into the resultant forces at the end-effector. The condition number of the Jacobian matrix gives a measure of the accuracy of end-effector control. It is desirable to design the robot to have a low condition number near unity so that the end-effector error is minimized. In addition, the condition number also indicates how close the given robot configuration is to the nearest singular configuration.

The Jacobian matrix for the 4R mechanism \( J \) is a 3×4 non-square matrix due to the redundant joint. Each column of \( J \) represents the relationship between the end-effector and one of the four revolute joints. (4.12) can be written as (4.14) where \( J = [J_1 \ J_2 \ J_3 \ J_4] \) and is a 3×4 matrix with \( J_1, J_2, J_3 \) and \( J_4 \) representing the relationships between the angular velocity of the 4R end-effector \( \omega \) and the angular rates \( \dot{\theta}_1, \dot{\theta}_2, \dot{\theta}_3 \) and \( \dot{\theta}_4 \) of Joints 1, 2, 3 and 4 respectively.

\[
\omega = [J_1 \ J_2 \ J_3 \ J_4] \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix} \tag{4.14}
\]

Due to the spherical nature of the 4R mechanism and the assignment of the DH coordinate systems at the ICOR, the Jacobian for each joint \( i \) can be obtained with (4.15) where \( n_z, o_z \) and \( a_z \) are obtained from the DH transformation matrix (4.16).

\[
J_i = \begin{bmatrix} n_z \\ o_z \\ a_z \end{bmatrix}_i \tag{4.15}
\]

\[
T^i_5 = \begin{bmatrix} n_x & o_x & a_x & r_x \\ n_y & o_y & a_y & r_y \\ n_z & o_z & a_z & r_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.16}
\]

The DH matrices of the 4R mechanism were presented in Section 3.4 and are repeated here for reference:

\[
T^0_1 = \begin{bmatrix} \cos \varphi_z & -\cos \varphi_x \sin \varphi_z & \sin \varphi_x \sin \varphi_z & 0 \\ \sin \varphi_z & \cos \varphi_x \cos \varphi_z & -\sin \varphi_x \cos \varphi_z & 0 \\ 0 & \sin \varphi_x & \cos \varphi_x & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.17}
\]
Multiplying these matrices and applying (4.15) gives the Jacobian terms in (4.22), (4.23), (4.24) and (4.25) where $S$ is the sine function and $C$ is the cosine function.

\[
J_1 = \begin{bmatrix}
-S\alpha_1(S\theta_2(C\theta_3 C\theta_4 - C\alpha_3 S\theta_3 S\theta_4) + C\alpha_2 C\theta_2(S\theta_3 C\theta_4 + C\alpha_3 C\theta_3 S\theta_4) - S\alpha_2 C\theta_2 S\alpha_2 S\theta_4) \\
-S\alpha_1(S\theta_2(-C\theta_3 S\theta_4 - C\alpha_3 S\theta_3 C\theta_4) + C\alpha_2 C\theta_2(-S\theta_3 S\theta_4 + C\alpha_3 C\theta_3 C\theta_4) - S\alpha_2 C\theta_2 S\alpha_2 C\theta_4) \\
-S\alpha_1(S\theta_2 S\alpha_3 S\theta_3 - C\alpha_2 C\theta_2 S\alpha_3 C\theta_3 - S\alpha_2 C\theta_2 C\alpha_3) + C\alpha_1(-S\alpha_2 C\alpha_3 C\theta_3 + C\alpha_2 C\alpha_3)
\end{bmatrix}
\] (4.22)

\[
J_2 = \begin{bmatrix}
S\alpha_2(S\theta_2 C\theta_4 + C\alpha_3 S\theta_3 S\theta_4) + C\alpha_2 S\alpha_3 S\theta_4 \\
S\alpha_2(-S\theta_3 S\theta_4 + C\alpha_3 C\theta_3 C\theta_4) + C\alpha_2 S\alpha_3 C\theta_4 \\
-S\alpha_2 S\alpha_3 C\theta_3 + C\alpha_2 C\alpha_3
\end{bmatrix}
\] (4.23)

\[
J_3 = \begin{bmatrix}
S\alpha_3 S\theta_4 \\
S\alpha_3 C\theta_4 \\
C\alpha_3
\end{bmatrix}
\] (4.24)

\[
J_4 = \begin{bmatrix}
0 \\
0 \\
1
\end{bmatrix}
\] (4.25)

By definition, the condition number is given by (4.26) where $\| \cdot \|$ is the norm of the matrix [106].

\[
k(J) = \| J \| \| J^{-1} \|
\] (4.26)

Given that the vector norms are Euclidean norms, the condition number becomes a measure of the ratio of the largest to the smallest singular value of the Jacobian matrix. These
singular values are determined by factorizing $J$ using the singular value decomposition rule in (4.27) where $X$ and $Y$ are orthogonal matrices and $\Sigma$ is a diagonal matrix of three singular values which are related as $\sigma_1 \geq \sigma_2 \geq \sigma_3 \geq 0$ [107].

$$[J]_{4\times3} = [X^T]_{4\times4}[\Sigma]_{4\times3}[Y]_{3\times3}$$  

(4.27)

The condition number of the Jacobian matrix $k(J)$ is then defined by (4.28) where the range of the condition number is given by (4.29).

$$k(J) = \frac{\sigma_1}{\sigma_3}$$  

(4.28)

$$1 \leq k(J) \leq \infty$$  

(4.29)

The condition number indicates how far away the specified configuration is from the nearest singular configuration. The closer the condition number is to unity, the further away the configuration is to a singular configuration. Therefore, the objective is to optimize the 4R mechanism to operate in configurations with a condition number value close to unity. This is a minimization problem.

The condition number is representative of a specific mechanism configuration therefore evaluation of a 4R design requires condition number analysis for each of the 89 discrete workspace positions. Although there can be loss of information in using a discretized workspace, simulations have shown that the values of condition number are quite similar in the neighborhood of any given point. Due to the kinematic redundancy of the 4R mechanism, a range of joint configurations are possible for reaching each workspace position. The optimization algorithm analyzes the range of possible configurations and selects the configuration with the best performance during the expanding algorithm outlined in Section 4.3.3. However, 89 condition numbers for a 4R design is not suitable for evaluating the overall performance of the design. To get a comprehensive summary of the condition number distribution over the shoulder workspace, the global condition number (GCN) (4.30) is used where $w$ is the reachable workspace.

$$\text{GCN} = \frac{\int_{w} k \; dw}{\int_{w} dw}$$  

(4.30)

To simplify the calculation, the GCN can be discretely defined as (4.31) where $k(j)$ is the condition number for the $j$th workspace position and $n$ is the total number of workspace positions.
The GCN has the same range of possible values as the condition number:

\[ 1 \leq GCN \leq \infty \]  

(4.32)

As with the condition number, a value of GCN near unity is desirable. This indicates the mechanism operates through most of the shoulder workspace without approaching a singular configuration. However, the GCN can overlook the occurrence of undesirable peak condition number values. To ensure these peak values are not overlooked, the maximum condition number value out of the 89 calculated for the workspace \( CN_{\text{max}} \) is also considered in the optimization process:

\[ CN_{\text{max}} = \max(k(1), \ldots, k(n)) \]  

(4.33)

The singularity objectives are therefore the minimization of the GCN and \( CN_{\text{max}} \).

### 4.5 Optimization Results

Design optimization of the 4R mechanism was carried out using the variables and objectives discussed throughout this chapter. The optimization problem is formulated as (4.34) where \( x \) is a solution in the population of solutions \( X \).

\[
\text{minimise} \quad F(x) = (f_{\text{ws}}(x), \Delta \theta(x), GCN(x), CN_{\text{max}}(x)) \\
\text{s.t.} \quad x \in X,
\]  

(4.34)

The average joint motion is obtained using (4.35).

\[ \Delta \theta(x) = \Delta \theta_{\text{ave}}(x) + \Delta \theta_{\text{max}}^4(x) \]  

(4.35)

The objective functions were formulated in MATLAB [108] and the NSGA II algorithm outlined in Section 4.1.1 was applied with a crossover probability of 0.9 and mutation probability of 0.167. The set of Pareto optimal solutions obtained at the conclusion of the NSGA II optimization are presented in Figure 4.11. To illustrate the Pareto front, the solutions are plotted in three separate graphs with each graph comparing a different pair of the three main objectives, namely GCN, \( CN_{\text{max}} \) and average joint motion. Each point in these graphs represents an optimal solution in the Pareto set which can be selected for the design of the 4R mechanism. Since all three performance criteria are minimization objectives, the Pareto front forms in the lower left region of each plot.
Table 4.2 lists 10 Pareto optimal solutions of the NSGA II optimization for a right shoulder 4R exoskeleton. For a left shoulder exoskeleton, the values for \( \varphi_x \) and \( \theta_1^0 \) are multiplied by negative one. Note that each solution is considered to perform equally well by the NSGA II algorithm. In this research, the 10th solution in Table 4.2 is selected for the design of the upper limb exoskeleton. This solution is selected because the sizes of the three links are smaller compared to the other solutions therefore an exoskeleton designed with these parameter values will have a lower weight. It is also possible to select a solution based on clinical input.

![Figure 4.11: Performance values of the Pareto optimal solutions obtained from the NSGA II optimization forms a Pareto front. (a) Maximum condition number and global condition number. (b) Average joint motion and global condition number. (c) Average joint motion and maximum condition number.](image)
4.5 Optimization Results

The optimal variable values of the selected solution are shown in Table 4.3. A 4R exoskeleton designed with these variable values can theoretically achieve 100% of the shoulder workspace without interfering with the user. Figure 4.12 shows a 4R exoskeleton with these parameter values.

Table 4.2: Ten Pareto optimal solutions

<table>
<thead>
<tr>
<th>Variables</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_1$</td>
<td>$\alpha_2$</td>
</tr>
<tr>
<td>92.1</td>
<td>79.7</td>
</tr>
<tr>
<td>88.6</td>
<td>81.2</td>
</tr>
<tr>
<td>77.3</td>
<td>89.6</td>
</tr>
<tr>
<td>94.0</td>
<td>80.2</td>
</tr>
<tr>
<td>104.3</td>
<td>79.9</td>
</tr>
<tr>
<td>80.5</td>
<td>94.7</td>
</tr>
<tr>
<td>83.5</td>
<td>90.7</td>
</tr>
<tr>
<td>77.1</td>
<td>89.6</td>
</tr>
<tr>
<td>95.0</td>
<td>79.7</td>
</tr>
<tr>
<td>88.9</td>
<td>79.9</td>
</tr>
</tbody>
</table>

Table 4.3: 4R variable values of the selected Pareto optimal solution

<table>
<thead>
<tr>
<th>Design Variable</th>
<th>Optimal Value (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_1$</td>
<td>88.9</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>79.9</td>
</tr>
<tr>
<td>$\alpha_3$</td>
<td>62.9</td>
</tr>
<tr>
<td>$\varphi_z$</td>
<td>9.0</td>
</tr>
<tr>
<td>$\varphi_x$</td>
<td>35.2</td>
</tr>
<tr>
<td>$\theta_1^0$</td>
<td>-149.0</td>
</tr>
</tbody>
</table>
For comparison, the optimization algorithm is applied to two other designs: a 4R mechanism with 90° link angles and the base joint behind the shoulder and a 3R mechanism with the base joint rotated 45° laterally from behind the shoulder. The GCN, $CN_{\text{max}}$ and average joint motion values for the three designs are shown in Table 4.4. However, for the analysis of the 3R mechanism, a workspace constraint that was imposed during the optimization of the 4R is removed. This constraint prevented the mechanism links from entering the region above the shoulder and is removed because it significantly reduced the workspace of the 3R mechanisms. As a result, the 3R mechanism will operate closer to the user’s head than the 4R mechanisms.

Table 4.4: Performance comparison between the 4R and 3R designs

<table>
<thead>
<tr>
<th>Design</th>
<th>GCN</th>
<th>$CN_{\text{max}}$</th>
<th>Average Joint Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimized 4R</td>
<td>1.7</td>
<td>2.4</td>
<td>0.162</td>
</tr>
<tr>
<td>4R with 90° links and base behind ICOR</td>
<td>1.9</td>
<td>5.0</td>
<td>0.242</td>
</tr>
<tr>
<td>3R with base rotated 45° laterally</td>
<td>2.4</td>
<td>8.0</td>
<td>0.250</td>
</tr>
</tbody>
</table>
Recall that the 4R mechanism configuration is further away from a singular configuration if the condition number value is closer to unity (refer to Section 4.4). The optimized 4R design has both a GCN and a $CN_{\text{max}}$ value that is closer to unity compared to the other designs. The lower GCN value of 1.7 for the optimized 4R compared to 1.9 for the un-optimized 4R and 2.4 for the 3R indicates that on average this 4R exoskeleton is able to operate further from singular configurations than the other designs when operating in the shoulder workspace. The small $CN_{\text{max}}$ value of 2.4 for the optimized 4R indicates that this design can achieve the entire shoulder workspace with configurations that are all relatively far from a singular configuration. The un-optimized 4R has a higher $CN_{\text{max}}$ value of 5.0 and therefore will operate in a configuration that is closer to a singular configuration than any of the optimized 4R configurations. The large $CN_{\text{max}}$ value for the 3R exoskeleton confirms that there is a region in the defined shoulder workspace that requires the 3R exoskeleton to operate very close to a singular configuration. This agrees with the analysis in Section 3.2 where it has been identified that this 3R design cannot avoid operating near a singular configuration in the shoulder workspace. Figure 4.13 shows the condition number values of the 89 workspace positions for each design.

From Figure 4.13a, it can be seen that the optimized 4R mechanism operates the closest to singular configurations when at the edge of the shoulder workspace. To demonstrate the optimized 4R mechanism’s poorest performance, an example of the trajectories of Joints 1, 2, and 3 in performing a circular movement of the upper arm along the edge of the shoulder workspace is presented in Figures 4.14 and 4.15. This circumduction movement involves approximately 360° rotation of the shoulder and is done with a near-constant velocity of 51.4°/s over 7 seconds. The peak 4R joint velocity during this movement occurs in Joint 2 at 76°/s which is 48% higher than the shoulder velocity. Joints 1 and 3 have slightly lower peak velocities at 65°/s and 63°/s respectively.

For comparison, the joint trajectories of the 3R mechanism when moving near its singular configuration are shown in Figures 4.16 and 4.17. The movement involves a constant velocity 180° shoulder flexion over 3.5 seconds in the vertical plane with a 35° medial offset from the anterior direction. This shoulder rotation velocity is chosen to match that of the circumduction movement to provide a meaningful comparison. Since the singular configuration of the 3R mechanism occurs 45° medially from the anterior direction, the 35° medial offset in flexion means the closest the mechanism will operate to the singular configuration is 10° which occurs when the upper arm is in the horizontal position. At this position, the peak 3R joint velocity occurs in Joint 1 at an extremely high 296°/s which is
4.5 Optimization Results

476% higher than the shoulder velocity. Joint 2 has a more reasonable peak velocity of 50°/s. That is, Joint 1 of the 3R mechanism is required to rotate at 296°/s to achieve a 51.4°/s shoulder flexion when passing the horizontal upper arm position. Such a high joint velocity is undesirable firstly because it makes the exoskeleton more dangerous and intimidating to the user and secondly because it is difficult to achieve such high velocities and accelerations in practice. Note that movements closer to the singular configuration will require even higher velocities. In contrast, the joint velocities of the optimized 4R mechanism are at comfortable and feasible values close to that of the upper arm itself.

Figure 4.13: Condition number results for the 89 workspace points of three different designs: (a) Optimized 4R, (b) 4R with 90° links and base joint behind the shoulder, and (c) 3R with the base joint rotated 45° laterally from behind the shoulder.
4.5 Optimization Results

Figure 4.14: Trajectory path for the optimized 4R mechanism where it operates closest to singular configurations. This movement is a constant velocity shoulder circumduction over 7 seconds. Each point indicates a position of the upper arm and 4R end-effector. The green point indicates the starting and ending position, the solid blue points indicate the positions at every time step of 1 second and the hollow points indicate the positions at every time step of 0.1 second.

In terms of joint movement, the optimized 4R design has a significantly lower average joint motion of 0.162 compared to 0.242 for the un-optimized 4R and 0.250 for the 3R design. This implies that on average the joints of the optimized 4R move at a lower velocity when moving the end-effector through the shoulder workspace compared to the other designs.

Figure 4.18 shows the optimal joint angles of Joints 1, 2 and 3 to reach each of the 89 end-effector positions in the shoulder workspace. These joint angles combine to give the optimal joint configurations selected by the optimization algorithm for the kinematically redundant 4R mechanism. 3D models of these 89 configurations can be found in Appendix A. From Figure 4.18, it can be seen that each joint can smoothly transition between adjacent end-effector positions in all directions without requiring sudden changes in joint angle. The optimal joint configuration for reaching an arbitrary end-effector position can be obtained by interpolating these 89 angles.
Figure 4.15: Position and velocity trajectories of Joints 1, 2 and 3 in the optimized 4R mechanism during the 7 second shoulder circumduction illustrated in Figure 4.14.
4.5 Optimization Results

Figure 4.16: Trajectory path for the 3R mechanism which passes near a singular configuration. This movement is a constant velocity 180° shoulder flexion over 3.5 seconds along the vertical plane with a 35° medial offset from the anterior direction. The red point represents the position in which a singular configuration of the 3R mechanism occurs.

Figure 4.17: Position and velocity trajectories of Joints 1 and 2 in the 3R mechanism during the 3.5 second shoulder flexion illustrated in Figure 4.16.
Figure 4.19 shows that the offset between the angular positions of Joint 4 and that of shoulder axial rotation is minimal for the majority of the workspace. The larger offset occurs at the workspace boundary in the horizontally extended positions and at the vertical flexed position. These boundary positions are very difficult to reach for a typical shoulder and should not be an issue. A small offset means that Joint 4 can be implemented using a small arc-shaped rail with an arc size similar to the range of motion of shoulder axial rotation. A small rail makes the exoskeleton easier for the user to don and does not have the problem that a circular rail has where the rail interferes with the user’s torso when the upper arm is lowered.

![Diagram of displacement angles](image)

Figure 4.18: Displacement angles of Joints 1, 2 and 3 to optimally reach each of the 89 end-effector positions. (a) Joint 1 displacements. (b) Joint 2 displacements. (c) Joint 3 displacements.
4.6 Chapter Summary

A redundant 4R spherical wrist mechanism has been proposed for a shoulder exoskeleton to solve the singularity and workspace limitations present in the 3R spherical wrist. The 4R mechanism has been optimized using the NSGA II multi-objective optimization algorithm to achieve the entire human shoulder workspace while operating far away from singular configurations and without interfering with the user. An optimal 4R design is obtained along with a set of optimal joint configurations for the 4R to reach 89 uniformly distributed end-effector positions (i.e. upper arm positions) in the shoulder workspace. The set of optimal joint configurations is obtained using an expanding algorithm developed specifically for this optimization problem which ensures feasible, low-velocity transitions between all adjacent end-effector positions. The optimal joint configuration for reaching an arbitrary end-effector position can be obtained by interpolating the set of 89 configurations.

Algorithms were developed to evaluate the performance of any given 4R design for the NSGA II algorithm. Considerations were made in the algorithm to ensure each joint of the 4R mechanism can transition feasibly throughout the workspace with low velocities. The range of motion requirement of Joint 4 is minimized by considering the drift in its range of motion relative to that of shoulder axial rotation, allowing a short rail to be used for implementing Joint 4 in the exoskeleton. This makes the exoskeleton easier to don and reduces its interference with the user. Singularity analysis is done using GCN which indicates the average singularity performance of the design over the shoulder workspace and using $CN_{\text{max}}$ which indicates the closest the 4R mechanism will operate to a singular configuration.
4.6 Chapter Summary

The resulting 4R design obtained from the optimization process is analyzed for 89 end-effector positions which confirm an improved singularity performance compared to the 3R design and an un-optimized 4R design. Simulations of the optimal joint configurations confirm feasible and smooth movements of each joint in the 4R mechanism throughout the shoulder workspace. From the presented results, it can be deduced that the peak velocities for the joints of the 4R mechanism are often lower than those for the 3R mechanism when performing the same end-effector movement. A reduction in velocity corresponds to a reduction in joint accelerations and therefore the system is easier to control and lower performance components can be used.
The designs of past upper limb exoskeleton robots are not capable of achieving the full range of motion of the human shoulder without manipulation restrictions. In this research, the use of a redundant 4R spherical wrist mechanism is proposed to overcome this limitation. In Chapter 4, the kinematic design of the 4R spherical wrist has been optimized using the NSGA II algorithm specifically for implementation in an exoskeleton’s shoulder complex. The optimized 4R design can theoretically operate in the full range of motion of the human shoulder while keeping well away from problematic singular configurations and without mechanical interference. However, numerous design factors must be considered when implementing this concept in a complete exoskeleton design to ensure it can operate effectively with a human user.

This chapter presents an active upper limb exoskeleton system that uses the optimized 4R mechanism for the shoulder complex. The kinematic structure of the exoskeleton is provided along with discussions of numerous important design considerations which ensure the exoskeleton can achieve the maximum range of motion and is easy to use. An overview of the exoskeleton system and the GUI developed for operating this exoskeleton are presented.
5.1 Exoskeleton Kinematic Design

The optimized 4R mechanism parameters obtained in Chapter 4 are used in the design of a 5 DOF active exoskeleton for the left upper limb. The previous parameters were defined for the right shoulder and are converted for the left shoulder in Table 5.1. The 4R mechanism for the left shoulder is shown in Figure 5.1.

The 5 DOF exoskeleton includes 4 DOF for actuating the 3 DOF spherical motion of the shoulder joint and 1 DOF for actuating elbow movements. In other words, the exoskeleton can perform shoulder flexion & extension, abduction & adduction, medial & lateral rotation and elbow flexion & extension movements. These 4 DOF produce the largest movements in the upper limb and recovery of these movements is considered highly important in improving upper limb function. The 3 DOF spherical movements of the wrist and 2 DOF translational movements of the shoulder contribute less to upper limb movements and are not implemented in the present exoskeleton prototype. Figure 5.2 shows a CAD model of the exoskeleton and Figure 5.3 shows a photo of the exoskeleton prototype used by a healthy subject.

The exoskeleton is designed to be used while the user is in a seated position to ensure the user does not sway from the proper usage position which causes misalignment and can lead to the user entering the hazardous operating space of the exoskeleton. The DH parameters of the 5 DOF exoskeleton are shown in Table 5.2 where the parameters for $i = 6$ represent the relationship between the coordinate system of Joint 5 and the coordinate system defined at the hand position. The angular parameters $\alpha_i$ and $\theta_i$ are obtained from the design optimisation of the 4R mechanism presented in Chapter 4. The length parameters are carefully chosen through 3D simulations of the exoskeleton to ensure the different components of the exoskeleton do not unintentionally interfere with one another or with the user while operating in the shoulder workspace. The assignment of the coordinate systems is shown in Figure 5.4.

<table>
<thead>
<tr>
<th>Design Variable</th>
<th>Optimal Value (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_1$</td>
<td>88.9</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>79.9</td>
</tr>
<tr>
<td>$\alpha_3$</td>
<td>62.9</td>
</tr>
<tr>
<td>$\varphi_x$</td>
<td>-9.0</td>
</tr>
<tr>
<td>$\varphi_y$</td>
<td>35.2</td>
</tr>
<tr>
<td>$\theta_1^0$</td>
<td>149.0</td>
</tr>
</tbody>
</table>
5.1 Exoskeleton Kinematic Design

Figure 5.1: The optimized 4R mechanism concept for the left shoulder.

Figure 5.2: The 5 DOF upper limb exoskeleton with a shoulder complex designed using the optimized 4R mechanism parameters. The exoskeleton structure is constructed almost entirely from aluminium plates to allow rapid prototyping and enable future modifications.
5.1 Exoskeleton Kinematic Design

Figure 5.3: The 5 DOF upper limb exoskeleton prototype used by a healthy subject.

Figure 5.4: Default configuration of the 5 DOF exoskeleton.
Table 5.2: DH parameters of the 5 DOF exoskeleton

<table>
<thead>
<tr>
<th>Link i</th>
<th>$a_i$ (m)</th>
<th>$a_i$ (°)</th>
<th>$d_i$ (m)</th>
<th>$\theta_i$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>35.2</td>
<td>0</td>
<td>-9.0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>-88.9</td>
<td>-0.440</td>
<td>$\theta_1$</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>79.9</td>
<td>-0.247</td>
<td>$\theta_2$</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>62.9</td>
<td>-0.137</td>
<td>$\theta_3$</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>-90.0</td>
<td>0.126</td>
<td>$\theta_4$</td>
</tr>
<tr>
<td>6</td>
<td>0.33</td>
<td>0</td>
<td>0</td>
<td>$\theta_5 - 90$</td>
</tr>
</tbody>
</table>

The parameters in Table 5.2 are assigned into the DH transformation matrices which are used in forward and inverse kinematics of the robot. The general form of the DH matrix is brought from Section 3.4 for reference:

$$T_{i-1}^i = \begin{bmatrix}
\cos \theta_i & -\cos \alpha_i \sin \theta_i & \sin \alpha_i \sin \theta_i & a_i \cos \theta_i \\
\sin \theta_i & \cos \alpha_i \cos \theta_i & -\sin \alpha_i \cos \theta_i & a_i \sin \theta_i \\
0 & \sin \alpha_i & \cos \alpha_i & d_i \\
0 & 0 & 0 & 1
\end{bmatrix} \quad (5.1)$$

The matrices representing the geometric relationship between each pair of adjacent coordinate systems now includes the parameters $d_i$ for the actual design which was omitted for simplicity during design optimization:

$$T_1^0 = \begin{bmatrix}
\cos \varphi_x & -\cos \varphi_x \sin \varphi_z & \sin \varphi_x \sin \varphi_z & 0 \\
\sin \varphi_x & \cos \varphi_x \cos \varphi_z & -\sin \varphi_x \cos \varphi_z & 0 \\
0 & \sin \varphi_x & \cos \varphi_x & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \quad (5.2)$$

$$T_2^1 = \begin{bmatrix}
\cos \theta_1 & -\cos \alpha_1 \sin \theta_1 & -\sin \alpha_1 \sin \theta_1 & 0 \\
\sin \theta_1 & \cos \alpha_1 \cos \theta_1 & \sin \alpha_1 \cos \theta_1 & 0 \\
0 & -\sin \alpha_1 & \cos \alpha_1 & d_1 \\
0 & 0 & 0 & 1
\end{bmatrix} \quad (5.3)$$

$$T_3^2 = \begin{bmatrix}
\cos \theta_2 & -\cos \alpha_2 \sin \theta_2 & \sin \alpha_2 \sin \theta_2 & 0 \\
\sin \theta_2 & \cos \alpha_2 \cos \theta_2 & -\sin \alpha_2 \cos \theta_2 & 0 \\
0 & \sin \alpha_2 & \cos \alpha_2 & d_2 \\
0 & 0 & 0 & 1
\end{bmatrix} \quad (5.4)$$

$$T_4^3 = \begin{bmatrix}
\cos \theta_3 & -\cos \alpha_3 \sin \theta_3 & \sin \alpha_3 \sin \theta_3 & 0 \\
\sin \theta_3 & \cos \alpha_3 \cos \theta_3 & -\sin \alpha_3 \cos \theta_3 & 0 \\
0 & \sin \alpha_3 & \cos \alpha_3 & d_3 \\
0 & 0 & 0 & 1
\end{bmatrix} \quad (5.5)$$
5.1 Exoskeleton Kinematic Design

\[
T_5^4 = \begin{bmatrix}
\cos \theta_4 & 0 & -\sin \theta_4 & 0 \\
\sin \theta_4 & 0 & \cos \theta_4 & 0 \\
0 & -1 & 0 & d_4 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\] (5.6)

\[
T_6^5 = \begin{bmatrix}
\cos(\theta_5 - 90) & -\sin(\theta_5 - 90) & 0 & a_5 \cos(\theta_5 - 90) \\
\sin(\theta_5 - 90) & \cos(\theta_5 - 90) & 0 & a_5 \sin(\theta_5 - 90) \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\] (5.7)

Note that the numbering of the parameters is delayed by one compared to the link number in Table 5.2 since the first line of parameters is used to define the orientation of Joint 1 with respect to the global coordinate system. Applying the geometric parameters of the exoskeleton design in (5.2) to (5.7), the following DH matrices which represent the kinematic structure of the exoskeleton are obtained:

\[
T_1^0 = \begin{bmatrix}
0.9877 & 0.0902 & 0.1278 & 0 \\
-0.1564 & 0.5693 & 0.8071 & 0 \\
0 & -0.8171 & 0.5764 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\] (5.8)

\[
T_2^1 = \begin{bmatrix}
\cos \theta_1 & -0.0192 \sin \theta_1 & -0.9998 \sin \theta_1 & 0 \\
\sin \theta_1 & 0.0192 \cos \theta_1 & 0.9998 \cos \theta_1 & 0 \\
0 & -0.9998 & 0.0192 & -0.440 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\] (5.9)

\[
T_3^2 = \begin{bmatrix}
\cos \theta_2 & -0.1754 \sin \theta_2 & 0.9845 \sin \theta_2 & 0 \\
\sin \theta_2 & 0.1754 \cos \theta_2 & -0.9845 \cos \theta_2 & 0 \\
0 & 0.9845 & 0.1754 & -0.247 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\] (5.10)

\[
T_4^3 = \begin{bmatrix}
\cos \theta_3 & -0.4555 \sin \theta_3 & 0.8902 \sin \theta_3 & 0 \\
\sin \theta_3 & 0.4555 \cos \theta_3 & -0.8902 \cos \theta_3 & 0 \\
0 & 0.8902 & 0.4555 & -0.137 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\] (5.11)

\[
T_5^4 = \begin{bmatrix}
\cos \theta_4 & 0 & -\sin \theta_4 & 0 \\
\sin \theta_4 & 0 & \cos \theta_4 & 0 \\
0 & -1 & 0 & 0.126 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\] (5.12)

\[
T_6^5 = \begin{bmatrix}
\cos(\theta_5 - 90) & -\sin(\theta_5 - 90) & 0 & 0.33 \cos(\theta_5 - 90) \\
\sin(\theta_5 - 90) & \cos(\theta_5 - 90) & 0 & 0.33 \sin(\theta_5 - 90) \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\] (5.13)
5.2 Design Considerations

There are numerous important design factors that must be considered in the design of the 5 DOF exoskeleton prototype to ensure it can achieve the required performance and is user friendly. These are discussed in the subsequent sections.

5.2.1 Mechanical interference

The exoskeleton must not collide with other parts of its structure or with the user while operating in the human upper limb workspace. This is particularly challenging for the shoulder mechanism of the exoskeleton since the shoulder has a very large range of motion which limits the space available for the exoskeleton structure and its components. In addition, there are many joints and links that move in close proximity to one another which increases the possibility of mechanical interference. Mechanical interference is considered during the design of the links and joints as well as in the selection of actuators and sensors.

End-effector positions reaching the edge of the shoulder workspace have been found to be the most likely to cause mechanical interference and are carefully considered during the design process. Figure 5.5 shows the final exoskeleton design at key end-effector positions along the edge of the shoulder workspace. It can be seen that interference does not occur and the exoskeleton can feasibly reach these extreme shoulder positions.

Interference analysis is done by simulating a 3D CAD model of the exoskeleton in the PTC Creo Parametric software [109]. Results show that unintentional interference does not occur for the 89 optimal joint configurations obtained from the NSGA II optimization. These 89 configurations are presented in Appendix A. Intentional interference such as the interference between the exoskeleton’s hand interface and the user’s torso when the hand is moved towards the torso is not considered a problem.

5.2.2 Range of motion of exoskeleton joints

The optimal configurations that the joints of the kinematically redundant 4R mechanism operate in were previously determined for 89 upper arm positions in the shoulder workspace (see Chapter 4). These configurations are used to identify the upper and lower angular displacement limits for Joints 1, 2 and 3 in the exoskeleton. The displacement limits for Joints 4 and 5 are directly related to the range of motion limits of shoulder axial rotation and elbow flexion & extension respectively and are chosen accordingly while ensuring mechanical interference does not occur. The clockwise and counter-clockwise angular displacement limits for each exoskeleton joint is shown in Table 5.3. The angles are with
5.2 Design Considerations

respect to the directional axis of the proximal link towards the previous joint when viewed from an external perspective.

Figure 5.5: The exoskeleton with the upper arm at four different positions along the edge of the shoulder workspace. These extreme positions can be feasibly reached by the exoskeleton without causing mechanical interference.
### 5.2 Design Considerations

#### Table 5.3: Range of motion of exoskeleton joints

<table>
<thead>
<tr>
<th>Exoskeleton Joint</th>
<th>Clockwise Limit (°)</th>
<th>Counter-Clockwise Limit (°)</th>
<th>Total Range of Motion (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14</td>
<td>-89</td>
<td>103</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
<td>-25</td>
<td>145</td>
</tr>
<tr>
<td>3</td>
<td>-57</td>
<td>-132</td>
<td>75</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
<td>-78</td>
<td>96</td>
</tr>
<tr>
<td>5</td>
<td>180</td>
<td>55</td>
<td>125</td>
</tr>
</tbody>
</table>

#### 5.2.3 Clearance to user’s upper limb

The exoskeleton segments are designed to maintain a safe distance away from the user during operation. This is especially important for the segments of the 4R mechanism (which do not match the movements of the user’s limb segments) as interference of these segments can cause injuries to the user. This includes the segments from Joint 1 to Joint 3 (see Figure 5.2) which are designed to operate a relatively large distance away from the user. The segments from Joint 3 onwards are designed to be closer to the user’s limb as these segments move with the user’s limb and therefore have a low risk of causing harmful interference to the user. This also makes it easier to physically couple the user’s limb to the exoskeleton segments. The smallest distance between the axis of the user’s limb and an exoskeleton link is 8 cm. This gives a clearance of approximately 4 cm for a typical user.

#### 5.2.4 Support frame

The exoskeleton base is supported by a mechanically grounded aluminium frame behind the user. This means that the user does not carry the weight of the exoskeleton but is instead supported by the exoskeleton during rehabilitation. Such support is important since the user’s upper limb is expected to have some level of impairment. Furthermore, reaction forces from the exoskeleton due to actuation are transmitted to the ground via this frame.

#### 5.2.5 Replaceable forearm link

This research focuses on developing an exoskeleton for the shoulder joint and the presented 5 DOF prototype does not include movements of the forearm, wrist or fingers. To allow for the inclusion of these joints in future developments, the forearm segment of the exoskeleton is designed to be easily replaceable.
5.2 Design Considerations

5.2.6 Joint alignment

An exoskeleton is designed to operate alongside the human limb with the exoskeleton joints aligned with the corresponding upper limb joints of the user. Operating the exoskeleton when there is a misalignment between the joints of the exoskeleton and the human limb causes the generation of undesirable interaction forces and limb positioning errors. Therefore, the exoskeleton structure is designed to keep all five joints aligned with the human counterpart throughout the entire upper limb workspace. Joints 1, 2, 3 and 4 correspond to the shoulder joint and are permanently aligned with the ICOR of the shoulder whereas Joint 5 is kept aligned with the user’s elbow joint.

To facilitate users with different arm lengths, links with adjustable lengths are used for the exoskeleton segments corresponding to the upper arm and forearm so that joint alignment can be maintained. In addition, the height of the exoskeleton can be adjusted at the support frame to align the shoulder joint when the user is in a seated position. These adjustments are achieved using passive linear slider mechanisms which are locked into position once they are adjusted to the correct lengths. Table 5.4 shows the typical human segment dimensions and the adjustable ranges of the corresponding exoskeleton segments. The lengths of the adult upper limb segments are obtained from average values in literature [110].

<table>
<thead>
<tr>
<th>Segment</th>
<th>Average Adult Dimensions</th>
<th>Exoskeleton Dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lower Limit</td>
</tr>
<tr>
<td>Shoulder ICOR to Elbow</td>
<td>278</td>
<td>255</td>
</tr>
<tr>
<td>Elbow to Palm</td>
<td>349</td>
<td>125</td>
</tr>
<tr>
<td>Shoulder to Ground</td>
<td>1000</td>
<td>800</td>
</tr>
</tbody>
</table>

Table 5.4: Dimensions of upper limb and exoskeleton segments

5.2.7 Design of Joint 4 for shoulder axial rotation

As a result of the optimization done in Chapter 4, the optimized 4R mechanism can maintain a close match between the drifting angular positions of Joint 4 and shoulder axial rotation throughout the shoulder workspace. This means the range of motion requirement of Joint 4 is close to that of shoulder axial rotation. Therefore, a relatively small rail can be used
which makes the exoskeleton easy to don and reduces the exoskeleton’s interference with the user.

Joint 4 in the 4R mechanism of the exoskeleton is implemented using a curved rail mechanism as opposed to the simple pin joints used for the other 4 DOF. The curved rail is achieved using a pinion gear engaged on a curved rack as shown in Figure 5.6. This mechanism converts the rotational motion of the motor into a translational motion along an arc around the upper arm. Thus, joint alignment is achieved without mechanical interference between the exoskeleton and the user.

The curved rail consists of two 60° curved rail segments (THK, Japan) \[111\] which gives an axial rotation range of motion close to 120°. The use of a 120° section as opposed to a 360° ring allows the user to easily don the exoskeleton without needing to make difficult maneuvers with the limb. In addition, the 120° rail is positioned lateral to the upper arm and therefore does not interfere with the torso whereas a 360° rail cannot avoid contact with the torso when the upper arm is lowered. A rail size of 120° is used as this size can achieve the range of motion of shoulder axial rotation without sacrificing the range of motion of other DOF due to mechanical interference of the rail with the user’s body. The center of the rail is offset posteriorly by 30° to match the shoulder range of motion. This also conveniently prevents the rail from interfering with the user’s head when flexing the shoulder to raise the upper arm above the horizontal plane.

Figure 5.6: The 120° curved rail mechanism for generating upper arm axial rotation used in Joint 4 of the 5 DOF exoskeleton.
5.3 Actuators and Sensors

Past upper limb exoskeletons most commonly use electric motors or PMA for actuation. The main advantages of PMAs are their high power-to-weight ratio and their mechanical compliance. However, the many drawbacks of PMAs make them not suitable for the upper limb exoskeleton. For every joint in the exoskeleton, a pair of PMA is required to enable bi-directional actuation. The 5 DOF exoskeleton has five joints in close proximity with each other and there is no space for five pairs of PMAs on the exoskeleton links. Furthermore, PMAs have a relatively small actuation range and is not suitable for actuating the shoulder joint which has a very large range of motion. PMAs also respond slowly to command signals and have non-linear actuation characteristics which make them difficult to control. In addition, PMAs are driven by compressed air which is noisy and inconvenient to supply.

In the case of motors, their lower power-to-weight ratio is not a major issue since the human upper limb is mainly used for precise movements over a large range of motion rather than load support and the motors do not need to be high power. Furthermore, it is possible to produce compliant behavior in a motor driven exoskeleton with the appropriate control strategies. Hence, motors are used for the actuation of the 5 DOF upper limb exoskeleton.

Sensors are installed on the exoskeleton to measure rotational displacement of the five exoskeleton joints and the interaction force between the user’s limb and the exoskeleton. Joint displacements are used in forward kinematics to determine the exoskeleton configuration and therefore the upper limb posture in real-time. Measurements of interaction force are used in the interactive control strategies presented in Chapter 7.

Further details on the selection of actuators and sensors are provided in Appendix B.

5.4 Human-Robot Interface

The human upper limb has 9 DOF which are located at the shoulder, elbow and wrist and is kinematically redundant. In other words, constraining the hand will still leave the upper arm and forearm free to move. Therefore, to kinematically resolve all 9 DOF of the entire upper limb, at least two physical HRI must be used. In the 5 DOF exoskeleton, the two HRI are located at the upper arm near the elbow and at the hand. The HRI at the upper arm consists of a platform and a strap to couple the arm to the exoskeleton between Joint 4 and Joint 5. The HRI at the hand consists of a handle and a platform to rest the hand. The two HRI are designed to allow the user to easily don the exoskeleton with minimal effort and
without the need to make difficult maneuvers with the arm. A two-axis force sensor is incorporated into the upper arm HRI to measure forces in the directions of shoulder flexion & extension and abduction & adduction. A one-axis force sensor is used in the hand HRI to measure elbow flexion & extension forces.

### 5.5 Safety Features

Safety is a major concern for any device that actively interacts with a human user. The actuated exoskeleton is physically coupled to the user’s upper limb and can cause severe injuries to the user in the event of an accident or malfunction. The fact that the exoskeleton can generate torques large enough to overpower users with severe upper limb impairment further increases the need for reliable safety measures. A number of features have been included in the exoskeleton system to ensure safe and comfortable operation for the user.

Mechanical stoppers are used at each of the five actuated joints to prevent the exoskeleton joints from moving beyond their standard operating range of motion. The software also monitors the position of each joint via the magnetic encoder sensors and prevents the motor from driving the joint beyond the range of motion limits. The range of motion limits for each of the five exoskeleton joints were presented in Table 5.3. Motor speeds are also limited by software. Emergency stop buttons are available for the exoskeleton user and external users to manually stop the exoskeleton if a problem occurs.

### 5.6 System Architecture

The exoskeleton system is controlled by a PC via USB. A microcontroller is used to communicate with each device in the exoskeleton. These include five motor controllers, five rotary encoders, one two-axis force sensor and one single-axis force sensor. A flow diagram showing the input/output (I/O) communication in the exoskeleton system is presented in Figure 5.7.

Digital communication with the magnetic encoder sensors and force sensors is implemented using an I2C bus [112]. The I2C protocol is an elegant method of implementing communication in a system with many devices such as the exoskeleton system. Furthermore, future addition of sensors or other devices into the system can be done simply by configuring the device with a unique address and connecting it to the I2C bus. The I2C bus in the present exoskeleton system is shown in Figure 5.8.
5.6 System Architecture

Figure 5.7: Exoskeleton system diagram.

Figure 5.8: The I2C bus in the exoskeleton system. This bus is used to communicate with five magnetic encoders and two force sensors.
5.7 Graphical User Interface

A graphical user interface (GUI) is developed in MATLAB for operating the 5 DOF exoskeleton (Figure 5.9). The GUI is used to:

- Switch between admittance and impedance control modes
- Enable and disable support of forearm and upper arm weight
- Plan a trajectory
- Visualize a 3D simulation of the trajectory before applying it on the exoskeleton
- Change user limb mass and length parameters
- Change assistance gain and artificial stiffness, damping and inertia constants

Admittance mode allows the user’s limb to physically move the exoskeleton whereas in impedance mode the exoskeleton moves the user’s limb through a trajectory path. Details on the trajectory planner and the control modes are presented in Chapter 6 and Chapter 7 respectively. Under impedance mode, a trajectory point is created by setting the target position of the 4 upper limb DOF and the desired travel time to reach this position. Subsequent target points are added to the sequence to create the trajectory plan. Once the trajectory plan is prepared, a smooth trajectory is calculated using the methods outlined in Chapter 6 and demonstrated in the 3D model for verification before performing the movements with the exoskeleton. The GUI provides an intuitive trajectory planning process by simplifying movements of the spherical shoulder into horizontal and vertical displacements.

The kinematic parameters of the user’s upper limb segments can either be entered manually or estimated. The inertial and kinematic parameters of each upper limb segment are approximated using the total body mass and height of the user respectively [110] using (5.14) to (5.25) where $UA$ refers to the upper arm, $FA$ refers to the forearm, $HA$ refers to the hand, $H$ is the height of the subject, $M$ is the total body mass of the subject, $l$ is the length of the segment, $d$ is the distance to the segment’s center of mass from the proximal joint, $m$ is the segment mass and $I$ is the inertia tensor of the segment. These parameters are used to determine the required torque to support the limb and in the controllers in Chapter 7.

\[ l_{UA} = 0.186 \, H \]  \hspace{1cm} (5.14)

\[ l_{FA} = 0.146 \, H \]  \hspace{1cm} (5.15)
\[ l_{HA} = 0.108 \, H \]  \hspace{1cm} (5.16)

\[ d_{UA} = 0.436 \, l_{UA} \]  \hspace{1cm} (5.17)

\[ d_{FA} = 0.43 \, l_{FA} \]  \hspace{1cm} (5.18)

\[ d_{HA} = 0.506 \, l_{HA} \]  \hspace{1cm} (5.19)

\[ m_{UA} = 0.0263 \, M \]  \hspace{1cm} (5.20)

\[ m_{FA} = 0.015 \, M \]  \hspace{1cm} (5.21)

\[ m_{HA} = 0.0059 \, M \]  \hspace{1cm} (5.22)

\[ I_{UA} = \begin{bmatrix} m_{UA}(0.282 \, l_{UA})^2 & 0 & 0 \\ 0 & m_{UA}(0.265 \, l_{UA})^2 & 0 \\ 0 & 0 & m_{UA}(0.153 \, l_{UA})^2 \end{bmatrix} \]  \hspace{1cm} (5.23)

\[ I_{FA} = \begin{bmatrix} m_{FA}(0.265 \, l_{FA})^2 & 0 & 0 \\ 0 & m_{FA}(0.108 \, l_{FA})^2 & 0 \\ 0 & 0 & m_{FA}(0.261 \, l_{FA})^2 \end{bmatrix} \]  \hspace{1cm} (5.24)

\[ I_{HA} = \begin{bmatrix} m_{HA}(0.266 \, l_{HA})^2 & 0 & 0 \\ 0 & m_{HA}(0.169 \, l_{HA})^2 & 0 \\ 0 & 0 & m_{HA}(0.222 \, l_{HA})^2 \end{bmatrix} \]  \hspace{1cm} (5.25)
Figure 5.9: GUI developed for operating the exoskeleton.
5.8 Chapter Summary

The design of a 5 DOF active upper limb exoskeleton prototype is presented in this chapter. This exoskeleton uses the optimized 4R spherical wrist obtained in Chapter 4 for the design of the shoulder complex. The kinematically redundant 4R mechanism allows the exoskeleton to achieve the entire range of motion of the human shoulder with no mechanical interference while staying well away from singular configurations. The result is an exoskeleton with 4 joints for actuating 3 DOF shoulder movements and 1 joint for actuating 1 DOF elbow movement.

Numerous important design factors were considered in realizing the final exoskeleton design to ensure it can operate effectively alongside a human user’s upper limb. Mechanical interference of the exoskeleton with other parts of its structure or with the user is carefully analyzed during all stages of the design. The exoskeleton is supported by a mechanically grounded frame so that it can support the user’s limb and reaction forces are transferred to the ground. Alignment between the joints of the exoskeleton and the corresponding joints of the upper limb is maintained throughout the workspace and several segments in the exoskeleton structure can be adjusted to facilitate users with different arm lengths. A curved rail encompassing the upper arm is used in Joint 4 for shoulder axial rotation. This joint design has minimal interference issues and allows the user to easily don the exoskeleton without the need to make complex maneuvers with the upper limb. A number of safety features are implemented in the exoskeleton system including mechanical stoppers at the joints, emergency stop buttons and software monitoring of the joint positions. To kinematically resolve the user’s upper limb, two HRI are used to constrain the user’s limb at the upper arm and hand. A GUI is developed to implement the trajectory planner in Chapter 6 and the interactive control strategies in Chapter 7.
Position control of industrial robot manipulators typically focuses on reaching a target position or moving with a constant velocity. However, in controlling the position of the upper limb exoskeleton robot, the velocity profile the robot moves with to reach the desired position is equally, if not more, important than the accuracy of the final position. The controller should move the user’s upper limb through a smooth trajectory and arrive at the desired position at a specified travel time, utilizing all the allocated time to make the trajectory as smooth as possible.

This chapter presents the minimum jerk trajectory planner which is developed to generate smooth trajectories for the 5 DOF upper limb exoskeleton. The minimum jerk criterion is derived from observing normal human motion and is therefore very suitable for formulating the trajectories of a rehabilitation exoskeleton. The minimum jerk criterion is firstly introduced using a simple point-to-point trajectory for the 1 DOF elbow joint. For the multi-DOF shoulder joint, the minimum jerk trajectory of the shoulder movement is determined and then converted to their respective exoskeleton joint trajectories. This involves using optimized data obtained from the optimization process in Chapter 4 to identify optimal inverse kinematics solutions of the redundant 4R shoulder mechanism.

A method is proposed to compute a single smooth trajectory from a given sequence of target positions and their corresponding arrival times. Considerations are made in the
algorithm to ensure overshoots do not occur in these trajectories. In the case of the multi-
DOF shoulder, a method is developed to allow smooth turning of the upper arm during its
spherical movements. These capabilities allow complex task-based movements to be easily
programmed and performed smoothly by the exoskeleton.

6.1 Minimum Jerk Trajectory

It is desirable to have the exoskeleton move with trajectories similar to the trajectories of
normal human movement to ensure the movements are comfortable and correct for
rehabilitation. From observations of voluntary movement, researchers have found that normal
human movements follow a trajectory that minimizes the total jerk [113, 114]. Jerk is the
time derivative of acceleration and is therefore the third time derivative of position \( x(t) \):

\[
\text{jerk} \quad \dddot{x}(t) = \frac{d^3 x(t)}{dt^3}
\]  (6.1)

A measure of smoothness can be obtained for a trajectory \( x \) that starts at time \( t_i \) and ends
at time \( t_f \) by calculating the jerk cost:

\[
\int_{t_i}^{t_f} (\dddot{x}(t))^2 \, dt
\]  (6.2)

To obtain the smoothest trajectory, it is necessary to optimize the trajectory function to
have the minimum jerk cost. The minimum jerk trajectory of an end-effector from one point
to another is obtained by minimizing the integral of the squared jerk over time. This
corresponds to the minimization of the function (6.3) where \( T \) is the terminal time at which
the target position \( x_T \), velocity \( \dot{x}_T \) and acceleration \( \ddot{x}_T \) are to be achieved when starting with
the initial position \( x_0 \), velocity \( \dot{x}_0 \) and acceleration \( \ddot{x}_0 \).

\[
I(x) = \frac{1}{2} \int_0^T (\dddot{x}_t)^2 \, dt
\]  (6.3)

The minimum of this function is found using calculus of variations. Firstly a function
(6.4) is defined for a trajectory \( x \) where \( \delta \) is an arbitrary function such that \( \delta_0 = \delta_T = 0 \),
\( \dot{\delta}_0 = \dot{\delta}_T = 0 \), \( \ddot{\delta}_0 = \ddot{\delta}_T = 0 \).

\[
h(\epsilon, t) = x(t) + \epsilon \delta(t)
\]  (6.4)
Let
\[ F(\epsilon) = \frac{1}{2} \int_{a}^{b} (\ddot{h})^2 \, dt \]  
(6.5)

The condition for the trajectory \( x \) to minimise \( I \) is
\[ \frac{dF(\epsilon)}{d\epsilon} \bigg|_{\epsilon=0} = 0 \]  
(6.6)

and so
\[ \frac{dF(\epsilon)}{d\epsilon} = \int_{0}^{T} (\dddot{x} + \epsilon \dddot{x}) \dddot{x} \, dt \]  
(6.7)

Using integration by parts
\[ \int_{0}^{T} \dddot{x} \dddot{x} \, dt = x_{0}^{[4]} \dddot{x}_{0}^{T} - \int_{0}^{T} x_{t}^{[4]} \dddot{x}_{t} \, dt \]  
(6.9)

Using integration by parts again
\[ -\int_{0}^{T} x_{t}^{[4]} \dddot{x}_{t} \, dt = -x_{t}^{[4]} \dddot{x}_{0}^{T} + \int_{0}^{T} x_{t}^{[5]} \dddot{x}_{t} \, dt \]  
(6.11)

Using integration by parts one last time
\[ \int_{0}^{T} x_{t}^{[5]} \dddot{x}_{t} \, dt = -\int_{0}^{T} x_{t}^{[6]} \dddot{x}_{t} \, dt \]  
(6.13)

Thus to satisfy the condition in (6.6) it is required that
\[ \int_{0}^{T} x_{t}^{[6]} \dddot{x}_{t} \, dt = 0 \]  
(6.14)

This must apply for arbitrary functions \( \delta \) therefore for all \( t \in [0,T] \)
\[ \dot{x}_{t}^{[6]} = 0 \]  
(6.15)
In other words, the minimum jerk trajectory occurs when the sixth time derivative of the trajectory function \( x \) is equal to zero. The general solution of this equation is a fifth-order polynomial in time (6.16), where \( a_0, a_1, a_2, a_3, a_4 \) and \( a_5 \) are six constants to be determined.

\[
x(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 \tag{6.16}
\]

\[
\dot{x}(t) = a_1 + 2a_2 t + 3a_3 t^2 + 4a_4 t^3 + 5a_5 t^4 \tag{6.17}
\]

\[
\ddot{x}(t) = 2a_2 + 6a_3 t + 12a_4 t^2 + 20a_5 t^3 \tag{6.18}
\]

The first three constants are obtained from the initial conditions \( t = 0 \)

\[
a_0 = x_0 \tag{6.19}
\]

\[
a_1 = \dot{x}_0 \tag{6.20}
\]

\[
a_2 = \frac{1}{2} \ddot{x}_0 \tag{6.21}
\]

The last three constants are determined from the terminal conditions \( t = T \)

\[
x_T = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4 + a_5 T^5 \tag{6.22}
\]

\[
\dot{x}_T = a_1 + 2a_2 T + 3a_3 T^2 + 4a_4 T^3 + 5a_5 T^4 \tag{6.23}
\]

\[
\ddot{x}_T = 2a_2 + 6a_3 T + 12a_4 T^2 + 20a_5 T^3 \tag{6.24}
\]

In matrix form

\[
\begin{bmatrix}
    x_T - a_0 - a_1 T - a_2 T^2 \\
    \dot{x}_T - a_1 - 2a_2 T \\
    \ddot{x}_T - 2a_2
\end{bmatrix}
= \begin{bmatrix}
    T^3 & T^4 & T^5 \\
    3T^2 & 4T^4 & 5T^5 \\
    6T & 12T^2 & 20T^3
\end{bmatrix}
\begin{bmatrix}
    a_3 \\
    a_4 \\
    a_5
\end{bmatrix} \tag{6.25}
\]

\[
\begin{bmatrix}
    a_3 \\
    a_4 \\
    a_5
\end{bmatrix} = \begin{bmatrix}
    T^3 & T^4 & T^5 \\
    3T^2 & 4T^4 & 5T^5 \\
    6T & 12T^2 & 20T^3
\end{bmatrix}^{-1}
\begin{bmatrix}
    x_T - a_0 - a_1 T - a_2 T^2 \\
    \dot{x}_T - a_1 - 2a_2 T \\
    \ddot{x}_T - 2a_2
\end{bmatrix} \tag{6.26}
\]

The six constants are then substituted into (6.16), (6.17) and (6.18) to obtain the minimum jerk trajectory in position, velocity and acceleration respectively.

Figure 6.1 shows an example of the minimum jerk trajectory for the 1 DOF elbow joint. In this example, the joint starts in a stationary position and rotate for 2 seconds to stop at the 90° position.
6.2 Trajectories for the Shoulder

The minimum jerk trajectory is calculated for the human user’s upper limb joints since the goal is to achieve smooth movement for the user. For the 5 DOF exoskeleton, this includes the 3 DOF shoulder joint and 1 DOF elbow joint. Deriving trajectories for the elbow joint is straightforward since the movement of the exoskeleton’s Joint 5 translates directly to movements of the elbow joint. In addition, the movement of Joint 4 also translates well to movements of shoulder axial rotation. As a result, minimum jerk trajectory can be calculated directly for these two exoskeleton joints which will translate to minimum jerk trajectory movement for the respective human limb joints.

Figure 6.1: Trajectory graphs in displacement, velocity, acceleration and jerk for the minimum jerk trajectory of the 1 DOF elbow joint moving from 0 to 90° in 2 seconds with a stationary start and end.
This is not the case for Joints 1, 2 and 3 in the 4R mechanism which are used to control the spherical position of the user’s upper arm in 2 DOF. The non-linear relationship between the motion of the shoulder joint and 4R mechanism means that even if the three exoskeleton joints are moving in their minimum jerk trajectories, the user’s shoulder joint will in most cases not be moving in its minimum jerk trajectory. Figures 6.2 and 6.3 illustrate this non-linear relationship where the human shoulder is moving with constant angular velocity while Joints 1, 2 and 3 of the exoskeleton are required to follow a non-linear trajectory in order to match the upper arm movement.

To achieve smooth movement of the shoulder, the minimum jerk trajectory must be computed for the 2 DOF shoulder movement (with axial rotation excluded) then converted to the respective trajectories of Joints 1, 2 and 3. These 2 DOF generate the spherical movement of the shoulder in 3D space and is typically described using a sequence of two Euler rotations. However, there are two problems with using Euler rotations to define a trajectory. Firstly, singularities can occur in Euler rotations. Secondly, unlike for translations in 3D space, rotations in 3D space are not commutative so the order in which the two Euler rotations are applied affects the outcome. This is fine when defining a spherical coordinate in 3D space but it is not suitable for defining a spherical trajectory since information on the path of the trajectory is required. The two Euler rotations represent the target position relative to the starting position but since they are not commutative, the two rotations cannot be applied simultaneously to find a direct trajectory path between the two positions.

Instead of using Euler rotations, the minimum jerk trajectory is derived for a single rotation of the upper arm from the starting position to the target position. The travel distance of the single rotation is the angle between the two positions about the ICOR. Firstly, the minimum jerk trajectory is computed for the one dimensional travel angle using the given travel time. The trajectory obtained represents the angular displacement from the starting position towards the target position over time. Using Quaternion rotation, these angular displacements are then used to rotate from the starting position about the rotation axis to find the upper arm positions for each instance in time. As a result, a set of upper arm positions over time is obtained which represents the minimum jerk trajectory.
6.2 Trajectories for the Shoulder

Figure 6.2: A 90° flexion of the shoulder joint from the lowered vertical position to the horizontal forward position in 2 seconds with constant velocity. The solid green point indicates the starting position of the upper arm and the solid blue point indicates the ending position. Each hollow point in the trajectory path represents a 0.1 second time step.

Figure 6.3: A constant velocity flexion of the shoulder joint is shown in the top graph with the corresponding trajectories for exoskeleton Joints 1, 2 and 3 shown in the bottom three graphs. The relationship between shoulder movement and the movement of exoskeleton joints is non-linear.
Next, the set of upper arm positions are converted to a respective set of Joint 1, 2 and 3 angles representing configurations of the 4R mechanism. However, the 4R mechanism is kinematically redundant therefore there are infinite configuration solutions that can achieve each upper arm position. To overcome this, an optimal 4R configuration has previously been identified for 89 upper arm positions in the workspace during optimization in Chapter 4. These 89 optimal configurations are each represented by a Joint 1 angle value and its respective upper arm position. The Joint 1 angle eliminates the redundancy in the mechanism and enables a configuration solution to be found via inverse kinematics. Inverse kinematics is performed using the modified FABRIK algorithm presented in Section 3.6 to compute the angles of Joints 2 and 3.

It is very likely that the upper arm position of interest is not among the 89 obtained during design optimization. In order to find the Joint 1 angle for an arbitrary upper arm position, the 89 sets of upper arm positions and their respective Joint 1 angles are interpolated. Natural neighbor interpolation is used to interpolate the scattered 3D data and estimate the value of Joint 1 angle for the given spherical coordinate of the upper arm position. In this interpolation method, the scattered data points are tessellated to form a network of tetrahedra using the Delauney criterion. These tetrahedra are used to define a network of Thiessen polyhedra (3D versions of a polygon) in a 3D Voronoi diagram. The polyhedras have all surfaces equidistant to two or more neighboring points. For a given input, natural neighbor interpolation finds the points closest to this input among the scattered data. A Thiessen polyhedra is also constructed for the input point with respect to its neighboring points. Weights are then applied to each neighbor point based on the proportion of overlap between the volume of the new input polyhedra and the volumes of each neighbor’s initial polyhedra. These weights are applied to their respective neighbor points to interpolate an output value for the given input values. This ensures the interpolated output will be within the range of the neighbor points.

Now, the desired upper arm position and the interpolated Joint 1 angle are used to derive the angles of Joints 2 and 3 through inverse kinematics with the modified FABRIK algorithm. Once this is done, the angles of Joints 1, 2 and 3 are determined for a given upper arm position. This process is repeated for the upper arm positions in each time step of the minimum jerk trajectory to obtain a corresponding set of angles for Joints 1, 2 and 3. These sets of angles represent the simultaneous trajectories required from the three exoskeleton joints to achieve the minimum jerk trajectory of the upper arm in moving to the specified target position in the specified travel time. An example is shown in Figures 6.4 and 6.5 where
a minimum jerk trajectory of the upper arm is presented along with the corresponding trajectories of Joints 1, 2 and 3.

6.3 Combining a Sequence of Movements

The methods described so far have only considered a single straight rotation from one position to another. It is more useful to have a sequence of movements passing a series of specified positions to simulate a task or an exercise. Therefore, given a series of target positions and target times to reach each position, a single trajectory should be computed that passes through each position at the specified times while minimizing the jerk cost.

However, if the minimum jerk trajectory is found for each path independently using zero starting and terminal velocities and accelerations, the joint will stop at each target position. To obtain a smooth trajectory, the position, velocity, and acceleration should be continuous throughout the entire trajectory. Therefore, each sub-trajectory should smoothly follow through to the next while passing through each target position at the target times without stopping. To achieve this, it is necessary to approximate the velocity and acceleration at the transition where one sub-trajectory ends and the next sub-trajectory begins. This transition velocity and acceleration is used as the terminal velocity and acceleration in the derivation of the minimum jerk trajectory for the initial sub-trajectory $i$ and used as the starting velocity and acceleration in the derivation of the subsequent sub-trajectory $i + 1$:

$$\dot{x}_i(t_T) = \dot{x}_{i+1}(t_0)$$

$$\ddot{x}_i(t_T) = \ddot{x}_{i+1}(t_0)$$

6.3.1 Cubic spline interpolation

The transition velocities and accelerations are obtained by approximating the entire trajectory using a cubic spline interpolation. The entire set of trajectory positions are fitted with a piecewise cubic spline that pass through all the points while minimizing bending. Each point-to-point segment is approximated by a polynomial that ensures continuity between segments. Polynomials of order 3 or higher are required to achieve continuity hence the use of a cubic spline. For $n$ points in the trajectory there are $n - 1$ intervals between them. A cubic polynomial is determined for each interval (6.29) where $S_i(t)$ is the polynomial segment between point $i$ and $i + 1$, and $a_i$, $b_i$, $c_i$ and $d_i$ are the polynomial coefficients.

$$S_i(t) = a_i(t - t_i)^3 + b_i(t - t_i)^2 + c_i(t - t_i) + d_i \quad \text{for } t \in [t_i, t_{i+1}]$$
6.3 Combining a Sequence of Movements

Figure 6.4: A 90° flexion of the shoulder joint from the lowered vertical position to the horizontal forward position in 2 seconds with minimum jerk. Note that the points near the starting and stopping positions are denser which indicate the acceleration and deceleration of the upper arm in the minimum jerk trajectory.

Figure 6.5: A minimum jerk trajectory of shoulder flexion from 0° (upper arm positioned downwards) to 90° (upper arm positioned forwards) is shown in the upper graph. The corresponding trajectories for exoskeleton Joints 1, 2 and 3 are shown in the lower three graphs.
6.3 Combining a Sequence of Movements

For the spline to pass through both the desired points, the following constraints are enforced for this segment:

\[ S_i(t_i) = x_i \]  \hspace{1cm} (6.30)

\[ S_i(t_{i+1}) = x_{i+1} \]  \hspace{1cm} (6.31)

In addition, to ensure each segment continues smoothly into the next segment, each segment must satisfy the following:

\[ \dot{S}_i(t_i) = \dot{S}_{i+1}(t_i) \]  \hspace{1cm} (6.32)

\[ \ddot{S}_i(t_i) = \ddot{S}_{i+1}(t_i) \]  \hspace{1cm} (6.33)

The combination of all piecewise segments from \( S_1 \) to \( S_{n-1} \) completes the spline. Cubic spline interpolation is done using the “spline” function in MATLAB.

6.3.2 Stationary end points

The trajectory should have a stationary start point and end point but this is not the case for the cubic spline generated in MATLAB. This is illustrated in the example shown in Figure 6.6 where a joint starts at 0°, moves to the 90° position at 2 seconds and arrives at the 180° position at 6 seconds. This represents a 180° movement over 6 seconds with a higher velocity at the start of the trajectory followed by a lower velocity later on. The “spline” function in MATLAB creates a “natural spline” which results in a straight line at both the start and the end of the spline where \( \ddot{x} \) is zero and \( \dot{x} \) is constant. However, to achieve a stationary point \( \dot{x} \) should be zero. To enforce this, an extra point is added slightly before the first point at the same position and another is added slightly after the final point at the same position. These additional points ensure the cubic spline will start and end with near zero velocity. The two points are removed once the cubic spline is generated.

The velocity and acceleration at each intermediate point in the cubic spline is used as the boundary conditions for computing the minimum jerk trajectories for each interval. Figure 6.7 shows an example of a multi-point trajectory where each point-to-point segment is a minimum jerk trajectory derived using the boundary conditions obtained from the cubic spline interpolation. The trajectory starts at 0° and passes the 30° position at 1 second, the 60° position at 2.5 seconds, and the 90° position at 3.5 seconds. This represents a 90° movement over 3.5 seconds with a high velocity at the start of the trajectory, followed by a decreased velocity, and then a higher velocity again before arriving at the 90° position.
6.3 Combining a Sequence of Movements

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Position (°)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td>180</td>
</tr>
</tbody>
</table>

Figure 6.6: Application of stationary end points. (a) Trajectory plan to move the joint from 0° at 0 seconds to 90° at 2 seconds and 180° at 6 seconds. (b) Cubic spline interpolation of the three points. (c) Cubic spline interpolation with points added slightly before the start of the trajectory and slightly after the end of the trajectory to create stationary start and end points.
6.3 Combining a Sequence of Movements

![Trajectory plan](image)

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Position (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>2.5</td>
<td>60</td>
</tr>
<tr>
<td>3.5</td>
<td>90</td>
</tr>
</tbody>
</table>

(a)

Figure 6.7: Smooth trajectory for a multi-point trajectory plan. (a) Trajectory plan to move the joint from 0° at 0 seconds to 30° at 1 second, 60° at 2.5 seconds and 90° at 3.5 seconds. (b) Plot of the target points, the cubic spline interpolation of these points with a stationary start and end, and the trajectory obtained by combining three minimum jerk trajectories (one between each pair of points) using velocity and acceleration boundary conditions obtained from the cubic spline interpolation.
6.3 Combining a Sequence of Movements

A pause in the trajectory can be achieved by setting two target points in the same position with the second point delayed by the desired pause time (see Figure 6.8). The transition velocity and acceleration are zero at the starting and ending points of the pause.

**Trajectory plan**

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Position (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
</tr>
<tr>
<td>4</td>
<td>90</td>
</tr>
</tbody>
</table>

(a)

![Figure 6.8: Trajectory with a pause. (a) Trajectory plan to move the joint from 0° at 0 seconds to 45° at 1 second, stay at 45° until 2 seconds and move to 90° at 4 seconds. (b) Plot of the target points, the cubic spline interpolation and the trajectory obtained by combining three minimum jerk trajectories.](image)
6.3.3 Trajectories with reversing movement

The cubic spline interpolation can cause an overshoot in the trajectory when the direction of movement is reversed. This overshoot in the cubic spline will translate to an overshoot in the final trajectory obtained using the minimum jerk criterion. An overshoot can occur either before or after an intermediate point where the target positions before and after this point are positioned in the same direction with respect to the intermediate point. A trajectory overshoot is not desirable since the joint moves further than the planned peak position. An example of an overshoot occurrence is shown in Figure 6.9b where the trajectory plan in Figure 6.9a is used. The joint starts at the 0° position and arrive at the 90° position at 4 seconds then returns to the 0° position at 6 seconds. This represents a movement to the 90° position followed by a faster reverse movement to return to the initial 0° position. Typically, when a trajectory that reverses upon arriving at a target position is set in the trajectory plan, the extreme target position is the furthest position the programmer wishes the joint to reach. For this reason, an overshoot should be prevented in all cases when a velocity reversal occurs.

To prevent overshoots, extra points are added slightly after each extreme point with the same position similar to how extra points were added to the start and end of the trajectory. These extra points will ensure the cubic spline will have a maxima or minima occurring effectively at the extreme points. Then, when applying the minimum jerk criterion, the velocity at the extreme point is set to zero while the acceleration from the cubic spline is used. The improved trajectory of the example is shown in Figure 6.9c where the overshoot no longer occurs.

6.3.4 Turning for 2 DOF spherical shoulder

As discussed in Section 6.2, a single point-to-point minimum jerk trajectory for the 2 DOF spherical shoulder is obtained using the displacement angle and the axis of rotation to get from the starting position to the target position. Unlike the 1 DOF case that can only move in either a clockwise or counter-clockwise direction, the 2 DOF spherical joint is two-dimensional and can turn in its trajectory path. Therefore, the target positions in the trajectory may not lie in a straight path in which case the trajectory will need to turn at the intermediate point. A sharper turn at an intermediate point will mean the trajectory should arrive at the point with a lower transition velocity.
6.3 Combining a Sequence of Movements

Trajectory plan

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Position (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
</tr>
</tbody>
</table>

(a)

Figure 6.9: Trajectory with overshoot. (a) Trajectory plan to move the joint from 0° at 0 seconds to 90° at 4 seconds and return to 0° at 6 seconds. (b) An overshoot occurs in the trajectory and the joint moves further than the specified 90° in the attempt to generate a smoother trajectory. (c) No overshoot in the trajectory. This is achieved by including an additional point slightly after the extreme position of 90° to make the cubic spline stationary at this point.
To approximate the transition velocity, the turn angle is considered by using the angle between the two axes of rotation of the two consecutive sub-trajectories. If the turn angle is equal to or greater than 90°, the trajectory is required to stop at the intermediate point to prevent overshoot so a transition velocity of zero is used. For a turn angle between 0° and 90°, the transition velocity is maximum at 0° and decreases with a cosine function up to 90°. The turn angle is obtained using the dot product of the two rotation axes (6.34) where A and B are the two rotation axis vectors and $\phi$ is the turn angle between A and B.

$$A \cdot B = \|A\| \|B\| \cos \phi$$  \hspace{1cm} (6.34)

If the rotation axes are unit vectors the dot product becomes:

$$A \cdot B = \cos \phi$$  \hspace{1cm} (6.35)

Therefore, the transition velocity for a turning point, $\omega_T$, is defined by a piecewise function (6.36) where $\omega_S$ is the transition velocity for the two sub-trajectories approximated from cubic spline interpolation while assuming they follow through in a straight path. These two cases are illustrated in Figure 6.10. A zero transition acceleration is used for all trajectories of the 2 DOF shoulder.

$$\omega_T = \begin{cases} \omega_S(A \cdot B) & \text{for } A \cdot B > 0 \\ 0 & \text{for } A \cdot B \leq 0 \end{cases}$$  \hspace{1cm} (6.36)

To demonstrate turning of the 2 DOF shoulder, Figures 6.11, 6.12 and 6.13 shows the trajectory of the upper arm along with the corresponding trajectories of Joints 1, 2 and 3 of the exoskeleton for performing shoulder circumduction where the upper arm makes a circular movement along the perimeter of the workspace. This example uses 8 points along the circular path with a roughly equal spacing between each point. This generates a smooth circular trajectory of the left upper arm in a clockwise direction from the user’s perspective where the upper arm begins and ends at the vertical lowered position. A smoother curvature can be achieved by specifying more intermediate points along the curved trajectory path.

Note that condition number results presented in Section 4.5 indicated the 4R mechanism operates the closest to singular configurations at the edge of the shoulder workspace. Therefore the trajectories of Joints 1, 2 and 3 in the circumduction movement is an indication of the 4R mechanism’s worst performance (i.e. highest joint velocities and accelerations compared to that of the user’s shoulder) the 4R operates with. It can be seen that all the joints move with reasonable velocities and accelerations and there are no issues in exoskeleton movement.
6.3 Combining a Sequence of Movements

Figure 6.10: A sequence of two consecutive spatial rotations of the upper arm (rotation $A$ from $p_1$ to $p_2$ and rotation $B$ from $p_2$ to $p_3$) with (a) Turn angle greater than 90° (i.e. $A \cdot B > 0$), (b) Turn angle smaller than 90° (i.e. $A \cdot B < 0$).
6.3 Combining a Sequence of Movements

Figure 6.11: Trajectory plan for 2 DOF shoulder circumduction along the edge of the shoulder workspace which starts and ends with the upper arm in the lowered position. Eight points are used to generate the trajectory where the green point indicates the starting and ending position and the blue points represent the intermediate target positions.

Figure 6.12: Path of the smooth trajectory for the circumduction trajectory plan in Figure 6.11. Each point in the trajectory path represents a 0.1 second time step.
Figure 6.13: Trajectory of exoskeleton Joints 1, 2 and 3 for achieving the shoulder circumduction trajectory shown in Figure 6.12.
6.4 Chapter Summary

Minimum jerk trajectory planning is used with the exoskeleton to generate a smooth trajectory profile for the user’s upper limb joints while passing through specified target positions at target times. A trajectory that minimizes the minimum jerk criterion is considered the smoothest trajectory that can be obtained for achieving the target goals.

The solution to the minimum jerk criterion is identified to be a position trajectory represented by a fifth-order polynomial in time. For the exoskeleton’s Joint 4 and 5, the minimum jerk trajectory can be found and applied without transformation since these joints have a near one-to-one relationship with their respective human limb joints, shoulder axial rotation and elbow flexion & extension. However, in the case of Joints 1, 2 and 3 which control the two-dimensional spherical position of the upper arm, the relationship is non-linear and consequently the minimum jerk trajectories of the exoskeleton joints do not translate to a minimum jerk trajectory of the upper arm. Therefore, the minimum jerk trajectory is firstly found for the upper arm which is then converted to the corresponding Joint 1, 2 and 3 trajectories. This involves inverse kinematics of the kinematically redundant 4R mechanism which is achieved by interpolating known optimal joint configurations obtained during NSGA II optimization followed by the application of the modified FABRIK algorithm.

A method is proposed to generate a single smooth trajectory from a sequence of target positions by using a series of minimum jerk trajectories derived for every point-to-point path. This requires an approximation of the transition velocity and acceleration at each intermediate point to ensure continuity of position, velocity and acceleration throughout the trajectory. This approximation is achieved using a piecewise cubic spline interpolation through all the points. To enforce stationary end points and prevent overshoot when the trajectory reverses direction of movement, extra points are temporarily added at these positions with a small time difference to ensure a minima or maxima occurs at the desired points in the cubic spline. Turning for the 2 DOF spherical shoulder is achieved by considering the turn angle between two consecutive rotation paths. The transition velocity for a turn angle between 0° and 90° is maximum at 0° and decreases with a cosine function to zero at 90°. A smoother curvature can be achieved by specifying more intermediate points along the curved trajectory path.

The strategies discussed in this chapter enables complex trajectories involving multiple point-to-point movements to be implemented smoothly by the exoskeleton. Experimental results from applying these trajectories on the exoskeleton system are presented in Chapter 7.
The physical interaction between the exoskeleton and the user can be classified into two main types. One type involves the exoskeleton actively moving the user’s limb and the other involves the exoskeleton moving in the direction of the force applied by the user. In both types of interaction, the impedance of the exoskeleton can be adjusted to modulate the softness of the interaction from the user’s perspective. This can enable a wide variety of rehabilitation processes to be realized. For stroke patients, the first type of interaction is expected to be most beneficial as this best mimics current rehabilitation exercises which focus on motion.

This chapter presents force-based control strategies that allow the exoskeleton to interact with and respond to the unpredictable behavior of the user’s limb. The concept of admittance and impedance in the interaction between two physical systems is discussed and applied to the upper limb and exoskeleton system. A dynamic model of the exoskeleton is presented and the derivations of torques from the motor, inertia, gravity and friction are given. The admittance and impedance controllers for the 1 DOF elbow joint are presented and experimental results with a healthy human subject are provided to demonstrate their performance. The controllers are then extended for the more complex spherical movements.
7.1 Impedance of Robot Manipulators

Advancements in robotic technology over the past decades have mainly focused on the area of industrial robots. In industrial applications, the robot’s purpose is typically for position control and it is treated as an isolated system with little to no consideration of its dynamic interaction with the environment. However, this type of control method is not suitable for a rehabilitation robot since the robot is required to physically interact with and respond to a human user. A strategy to control the dynamic interactions between the robot and the human limb is required.

Interacting physical systems can be classified into two types, an admittance which accepts effort inputs (such as force) and produce flow outputs (such as motion) or an impedance which accepts flow inputs and produce effort outputs [115-117]. For a mechanical interaction between two physical systems, one system must physically complement the other. In other words, if one system is behaving as an impedance then the other must behave as an admittance. For an industrial robot manipulator, the environment is a physical system that accepts forces applied to it and produces motion in response. Therefore, the robot’s environment is described as an admittance. To ensure physical compatibility between the robot and its environment, the robot should assume the behavior of an impedance.

7.1.1 Impedance of an exoskeleton

In the case of an exoskeleton robot, both the robot and the user can behave as an impedance and impose motion. Therefore, the exoskeleton can operate in two distinct control modes. The first is admittance control in which the exoskeleton assumes the behavior of an admittance and moves when a force is applied to it by the user’s limb which is behaving as an impedance. In other words, the user’s limb imposes the position of the combined system of the upper limb and exoskeleton. The second control mode is impedance control in which the exoskeleton assumes the behavior of an impedance and applies force to the user’s limb through motion of its structure. Unlike traditional position control which ignores dynamic interactions with the environment, impedance control also allows modulation of the robot’s impedance behavior. A reduction in robot impedance will allow user-generated forces to have
an effect on the robot’s position. In other words, the exoskeleton imposes the position but the system can deviate from this position when force is applied by the user. This allows the exoskeleton to achieve position control with an artificial compliance or softness when interacting with the user’s limb.

7.2 Dynamic Model

The kinematic model of the 5 DOF exoskeleton was presented in Chapters 3 and 5. This section discusses the dynamic modeling of the exoskeleton and the upper limb. The Newton-Euler method is used to derive the equations of motion for each exoskeleton joint (7.1) where \( \tau_a \) is the actuation torque produced by the motor-gearbox unit, \( \tau_i \) is the torque due to inertia, \( \tau_g \) is the torque caused by gravitational forces, \( \tau_f \) is the friction torque and \( \tau_d \) is the disturbance torque caused by the user’s limb movements.

\[
\tau_a = \tau_i + \tau_g + \tau_f + \tau_d \quad (7.1)
\]

Torque caused by Coriolis and centrifugal effects are small since the exoskeleton operates at low velocities and are assumed to be negligible.

7.2.1 Actuator torque

The torque output of the brushless DC motors used in the exoskeleton joints is described by (7.2) where \( \tau_m \) is the output torque of the motor, \( k_t \) is the torque constant of the motor and \( i \) is the electrical current.

\[
\tau_m = k_t i \quad (7.2)
\]

The torque constants for each joint motor in the present exoskeleton design are given in Table 7.1. The gearbox attached to each motor increases the output torque while decreasing the output velocity. The output torque of the gearbox is given by (7.3) where \( \eta \) is the gearbox efficiency and \( r \) is the gearbox reduction.

\[
\tau_a = \eta r \tau_m \quad (7.3)
\]

The gearbox output torque can then be described by (7.4) where \( k_r \) is the gearbox reduction constant given by (7.5).

\[
\tau_a = k_r \tau_m \quad (7.4)
\]

\[
k_r = \eta r \quad (7.5)
\]
7.2 Dynamic Model

Using (7.2), the output torque at the joint becomes:

\[ \tau_a = k_r k_l l \quad (7.6) \]

The motor and gearbox combinations were carefully selected during design to ensure their reduction ratio and efficiency allows the motor to operate the joints at the required velocities and torques while their size and weight allows them to be mounted on the exoskeleton joints without causing interference problems. The gearbox reduction ratio of each motor is given in Table 7.1.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Maxon Motor</th>
<th>Torque Constant (k_t) (mNm/A)</th>
<th>Gear Reduction (r) (r:1)</th>
<th>Efficiency (\eta)</th>
<th>Reduction Constant (k_r)</th>
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<tr>
<td>1</td>
<td>EC 45 Flat 24V</td>
<td>33.5</td>
<td>156</td>
<td>0.72</td>
<td>132.4</td>
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<td>78.8</td>
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<tr>
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<td>EC 45 Flat 24V</td>
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<td>319</td>
<td>0.64</td>
<td>255.2</td>
</tr>
<tr>
<td>4</td>
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<td>33.5</td>
<td>47 (+282)</td>
<td>0.76</td>
<td>41.0 (+245.8)</td>
</tr>
<tr>
<td>5</td>
<td>EC 45 Flat 24V</td>
<td>33.5</td>
<td>156</td>
<td>0.72</td>
<td>132.4</td>
</tr>
</tbody>
</table>

*Value after a further reduction of 6:1 is applied to Joint 4 by the curved rail mechanism.

7.2.2 Inertial torque

The inertial torque experienced by an exoskeleton joint is given by (7.7) where \(I_s\) is the inertia tensor of the segment \(s\) at the joint coordinate system, \(\alpha\) is the angular acceleration of the joint and \(N\) is the total number of segments acting on the joint.

\[ \tau_l = \sum_{s=1}^{N} I_s \times \alpha \quad (7.7) \]

The inertial parameters for the exoskeleton and upper limb segments are presented in Table 7.2. The mass, center of mass and inertia tensor at the center of mass for each exoskeleton segment are obtained from a 3D model of the 5 DOF exoskeleton in Creo Parametric. For the human limb segments, inertial parameter values for an average adult are obtained from literature [110]. The wrist joint is assumed to be fixed at the normal anatomical position in the model.
### Table 7.2: Inertial parameters of the exoskeleton and upper limb

<table>
<thead>
<tr>
<th>Segment</th>
<th>Mass (kg)</th>
<th>Center of Mass (m from proximal joint)</th>
<th>Inertia Tensor at COM (kg m²²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link 1</td>
<td>2.34</td>
<td>(0, 0.282, -0.371)</td>
<td>$\begin{bmatrix} 0.0711 &amp; 0 &amp; 0 \ 0 &amp; 0.0461 &amp; 0.0315 \ 0 &amp; 0.0315 &amp; 0.0264 \end{bmatrix}$</td>
</tr>
<tr>
<td>Link 2</td>
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<td>(0, -0.168, -0.184)</td>
<td>$\begin{bmatrix} 0.0140 &amp; 0 &amp; 0 \ 0 &amp; 0.0075 &amp; -0.0057 \ 0 &amp; -0.0057 &amp; 0.0070 \end{bmatrix}$</td>
</tr>
<tr>
<td>Link 3</td>
<td>0.80</td>
<td>(0.017, -0.093, -0.005)</td>
<td>$\begin{bmatrix} 0.0028 &amp; 0 &amp; 0 \ 0 &amp; 0.0020 &amp; 0 \ 0 &amp; 0 &amp; 0.0039 \end{bmatrix}$</td>
</tr>
<tr>
<td>Link 4</td>
<td>1.57</td>
<td>(0, 0.141, 0.070)</td>
<td>$\begin{bmatrix} 0.0046 &amp; 0 &amp; 0 \ 0 &amp; 0.0032 &amp; 0 \ 0 &amp; 0 &amp; 0.0021 \end{bmatrix}$</td>
</tr>
<tr>
<td>Link 5</td>
<td>0.18</td>
<td>(0.027, -0.161, 0)</td>
<td>$\begin{bmatrix} 0.0025 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0.0026 \end{bmatrix}$</td>
</tr>
<tr>
<td>Upper arm</td>
<td>1.71</td>
<td>0.141</td>
<td>$\begin{bmatrix} 0.0143 &amp; 0 &amp; 0 \ 0 &amp; 0.0126 &amp; 0 \ 0 &amp; 0 &amp; 0.0042 \end{bmatrix}$</td>
</tr>
<tr>
<td>Forearm</td>
<td>0.98</td>
<td>0.109</td>
<td>$\begin{bmatrix} 0.0044 &amp; 0 &amp; 0 \ 0 &amp; 0.0007 &amp; 0 \ 0 &amp; 0 &amp; 0.0043 \end{bmatrix}$</td>
</tr>
<tr>
<td>Hand</td>
<td>0.38</td>
<td>0.095</td>
<td>$\begin{bmatrix} 0.0010 &amp; 0 &amp; 0 \ 0 &amp; 0.0004 &amp; 0 \ 0 &amp; 0 &amp; 0.0007 \end{bmatrix}$</td>
</tr>
</tbody>
</table>

The position and orientation of the segments change during operation therefore the inertia tensor of these segments with respect to the exoskeleton joints will also change. To determine the inertia tensor of each segment with respect to the joint coordinate system, the center of mass of the segment with respect to the joint coordinate system is firstly determined through forward kinematics. The inertia tensor at the segment’s center of mass is then transformed to the joint coordinate system by a rotation and a translation. The rotation of the inertia tensor is achieved using a similarity transformation (7.8) where $I_R$ is the inertia tensor that has been rotated into the orientation of the joint coordinate system, $I_m$ is the inertia tensor at the segment’s center of mass in the segment’s coordinate system and $R$ is the rotation matrix relating the segment coordinate system to the joint coordinate system.
\[ I_R = R I_m R^T \] (7.8)

Translation of the inertia tensor involves using the Parallel Axis Theorem (7.9) where \( I_T \) is the inertia tensor that has been translated into the origin of the joint coordinate system, \( m \) is the segment mass, \( p_m \) is the displacement vector from the center of mass of the segment to the origin of the joint coordinate system and \( I_3 \) is the \( 3 \times 3 \) identity matrix.

\[ I_T = I_m + m \left[ (p_m^T p_m) I_3 - p_m p_m^T \right] \] (7.9)

The inertia tensor of a segment with respect to the joint coordinate system can be obtained by applying the rotation followed by the translation:

\[ I_s = R I_m R^T + m \left[ (p_m^T p_m) I_3 - p_m p_m^T \right] \] (7.10)

Since the translation is applied after the rotation, \( p_m \) here is expressed in the joint coordinate system.

### 7.2.3 Gravity compensation

As with inertial torque, the torque caused by gravitational effects also depends on the configuration of the exoskeleton. The gravitational torque acting on an exoskeleton joint is given by (7.11) where \( p_s \) is the displacement vector from the joint to the center of mass of segment \( s \), \( m_s \) is the mass of the segment, \( R_s \) is the rotation transformation matrix between the global coordinate system and the joint coordinate system and \( g \) is the gravitational constant vector in the global coordinate system.

\[ \tau_g = \sum_{s}^N p_s \times (m_s(R_s g)) \] (7.11)

### 7.2.4 Friction compensation

Friction is a resistance to joint motion and is present in the motor, gearbox, bearings and the Joint 4 rail. In the present work, friction is modeled using a piecewise function (7.12) where \( k_f \) is the positive torque constant determined experimentally. The friction torque is assumed to act in the direction opposite to joint motion and if the joint is stationary then the friction torque is considered to be acting opposite to the direction of the control output.

\[ \tau_f = \begin{cases} k_f & \text{if } (\dot{\theta} < 0) \text{ or } (\dot{\theta} = 0 \text{ & } \tau_m < 0) \\ 0 & \text{if } (\dot{\theta} = 0) \text{ & } (\tau_m = 0) \\ -k_f & \text{if } (\dot{\theta} > 0) \text{ or } (\dot{\theta} = 0 \text{ & } \tau_m > 0) \end{cases} \] (7.12)
7.3 Control of the Elbow Joint

The 1 DOF elbow flexion & extension movements are controlled by Joint 5 in the exoskeleton. Control strategies are firstly discussed for this simpler 1 DOF joint before addressing the more complex multi-DOF shoulder mechanism.

7.3.1 Admittance control

In admittance control mode, the exoskeleton assumes the behavior of an admittance and its movements are determined by the external force applied to it by the user’s limb. With gravity and friction compensation, the exoskeleton joint will be stationary when there is no interaction force and moves when a light force is applied at the hand HRI. This makes the motorized joint feel like a lightweight and unconstrained joint from the user’s perspective. The interaction force is perceived by the user as a small resistance to movement. Furthermore, if gravity compensation of the user’s limb is enabled, the exoskeleton will support the relaxed limb at its current position and can assist the weak movements of the impaired limb. The control scheme of admittance mode is presented in Figure 7.1.

Admittance control of the 1 DOF elbow joint is implemented by using the force sensor readings as a control signal for the motor at Joint 5. A gain is applied to the force signal to drive the motor in the direction of the force using (7.13) where $\tau_{adm}$ is the torque output of the admittance controller, $k_{adm}$ is the admittance gain, $d_{HRI}$ is the displacement vector between the joint axis and the location of the interaction force and $F_{HRI}$ is the interaction force vector measured by the force sensor.

$$\tau_{adm} = k_{adm}(d_{HRI} \times F_{HRI})$$ (7.13)

![Figure 7.1: The control scheme of admittance mode.](image-url)
7.3 Control of the Elbow Joint

A higher gain will cause the resistance to movement to feel smaller to the user and vice versa. However, if the gain is too high the exoskeleton will move faster than the user. This causes a reversal of the interaction force as the interaction switches from that of a ‘push’ to a ‘pull’ which in turn causes the exoskeleton joint movement to reverse. The exoskeleton movement is then opposite to that of the user’s movement and the interaction switches from a ‘pull’ back to a ‘push’, causing another reversal of joint movement. As a result, the exoskeleton joint will produce an oscillating output. Therefore, a suitable gain is one that is high to reduce the resistance to movement but not so high that it causes the exoskeleton to move faster than the user.

To demonstrate admittance control, force is applied at the hand HRI by a healthy human subject to move Joint 5 by 90° and back as shown by the graphs in Figure 7.2. The peak force occurs only for a short instant and drops soon after due to the friction compensation. After this, force is required to keep the joint moving and the joint stops when the force is removed. For comparison, Figure 7.3 shows the same experiment with the back-drivable motor switched off (i.e. no admittance control). It can be seen that this requires approximately three times the peak force that occurred with admittance control and this high force is required throughout the entire movement.

The resistance to movement is low in full admittance mode but it is possible to increase the impedance of the exoskeleton to produce an artificial resistive behavior. This artificial resistance can be implemented in two different forms, namely an artificial damping which is a function of joint velocity and an artificial inertia which is a function of joint acceleration. These are expressed in (7.14) and (7.15) where $\tau_{imp,c}$ and $\tau_{imp,i}$ are the resistive torques from the artificial damping and inertia respectively, $k_c$ is the artificial damping constant and $k_i$ is the artificial inertia constant.

$$\tau_{imp,c} = -k_c \dot{\theta}$$  \hspace{1cm} (7.14)

$$\tau_{imp,i} = -k_i \dot{\theta}$$  \hspace{1cm} (7.15)

This gives the controller output torque as:

$$\tau_{adm} = k_{adm}(d_{HRI} \times F_{HRI}) - k_c \dot{\theta} - k_i \dot{\theta}$$  \hspace{1cm} (7.16)

An example of admittance control with artificial damping is shown in Figure 7.4 where the movement requires a constant force to be applied. Figure 7.5 shows admittance control with artificial inertia. Here, it can be seen that a peak force occurs indicating the sudden
acceleration of the inertia. The joint also continues to move after the force is removed but with a decelerating velocity as expected.

Figure 7.2: An example of user-generated movement in admittance control. Force is applied at the hand HRI (top graph) to move Joint 5 from 0° to approximately the -90° position and back (bottom graph).
Figure 7.3: An example of user-generated movement with no exoskeleton actuation. Force is applied at the hand HRI (top graph) to move Joint 5 from 0° to approximately the -90° position and back (bottom graph).
7.3 Control of the Elbow Joint

Figure 7.4: An example of user-generated movement in admittance control with artificial damping. Force is applied at the hand HRI (top graph) to move Joint 5 from 0° to approximately the -90° position and back (bottom graph).
Figure 7.5: An example of user-generated movement in admittance control with artificial inertia. Force is applied at the hand HRI (top graph) to move Joint 5 from 0° to approximately the -90° position and back (bottom graph).
7.3 Control of the Elbow Joint

### 7.3.2 Impedance control

In impedance control mode, the exoskeleton assumes the behavior of an impedance and moves to impose a position on the user’s limb. When the use’s limb is relaxed, it is behaving as an admittance and the exoskeleton acting as an impedance will achieve a performance similar to normal position control. However, when the user tries to move the limb, the limb can be seen to have an increase in impedance but if the exoskeleton is operating with high impedance it will not respond to the user’s force exertions. To allow the user to interact with the exoskeleton, the exoskeleton can operate with a reduced impedance so that the limb can have some control of position. Modulation of impedance allows user-generated forces to cause a deviation from the joint’s target position. This effectively produces an artificial compliance or softness in the interaction between the user’s limb and the exoskeleton.

A reduced impedance causes the exoskeleton to produce a smaller corrective response to position error caused by user-generated forces. Consequently, there becomes a trade-off between allowable interaction force and allowable deviation from the desired position which is analogous to the behavior of a spring. Therefore, joint impedance can be modulated by introducing an artificial stiffness in the controller (7.17) where \( \tau_{imp,k} \) is the opposing torque from the artificial stiffness, \( k_k \) is the artificial stiffness constant, \( \theta \) is the current joint position and \( \theta_t \) is the target joint position. The trade-off relationship between interaction force and position error can then be adjusted by changing the artificial stiffness constant.

\[
\tau_{imp,k} = -k_k(\theta - \theta_t)
\]  

(7.17)

Unfortunately, if joint stiffness is reduced, the position tracking performance will degrade. This is fine for a stationary target position but the joint will be unable to accurately follow a specified trajectory even when there is no interaction with the user’s limb. To overcome this, the admittance controller is used to amplify the influence of the user-generated forces. As a result, the artificial stiffness will be high enough to accurately track a target trajectory and only the amplified user-generated force can cause the joint to significantly deviate from its trajectory.

The control scheme of impedance mode is shown in Figure 7.6. Examples of impedance control are provided in the following Figures. Figure 7.7 shows the behavior of Joint 5 at a stationary target position when force is applied at the hand HRI. Figure 7.8 shows force applied while Joint 5 is following a trajectory path with low stiffness. Impedance control results for various types of trajectories derived from the smooth trajectory planner in Chapter 6 are presented in Figures 7.9 to 7.12.
7.4 Control of the Redundant Shoulder Mechanism

The kinematically redundant 4R mechanism in the exoskeleton is used to control the 3 DOF shoulder movements, namely shoulder flexion & extension, abduction & adduction and axial rotation. In the 5 DOF exoskeleton prototype, Joint 4 in the exoskeleton can independently control shoulder axial rotation. However, measuring interaction force for this DOF at the upper arm HRI is not reliable since slipping can occur between the upper arm and the HRI during axial rotation. Alternatively, force can be measured at the hand HRI but it becomes challenging to distinguish the force caused by shoulder axial rotation from forces caused by other upper limb DOF. Therefore, in the present exoskeleton only position control is implemented for Joint 4 and force-based control methods are not used.
Figure 7.7: An example of user-generated force applied in impedance control with a stationary target position. Force is applied at the hand HRI (top graph) which causes Joint 5 to deviate from its stationary target position (bottom graph).
Figure 7.8: An example of user-generated force applied while impedance control is following a trajectory with low stiffness. The force applied at the hand HRI (top graph) causes Joint 5 to deviate from its path (bottom graph).
7.4 Control of the Redundant Shoulder Mechanism

Figure 7.9: An example of impedance control following a smooth point-to-point trajectory with a target at -90° in 2 seconds.

Figure 7.10: An example of impedance control following a smooth trajectory with acceleration. Trajectory targets are set at -45° in 2 seconds and -90° in 3 seconds.
7.4 Control of the Redundant Shoulder Mechanism

Figure 7.11: An example of impedance control following a smooth trajectory with reversing direction of motion. Trajectory targets are set at -90° in 2 seconds, 0° in 4 seconds, -90° in 6 seconds and 0° in 8 seconds.

Figure 7.12: An example of impedance control following a smooth trajectory with a pause during motion. Trajectory targets are set at -45° in 2 seconds, -45° in 3 seconds and -90° in 5 seconds.
7.4 Control of the Redundant Shoulder Mechanism

A 2-axis force sensor has been integrated into the upper arm HRI to measure forces generated by the 2 DOF spherical movements of the upper arm, namely shoulder flexion & extension and abduction & adduction. However, the measured two-dimensional force does not translate linearly to the exoskeleton joints as was the case with the 1 DOF elbow. Furthermore, the 4R shoulder mechanism is kinematically redundant and there are infinite inverse kinematics and inverse dynamics solutions. To overcome these issues, the measured two-dimensional force is used to shift the target position of the upper arm rather than derive the exoskeleton joint outputs. The target upper arm position is then used to determine the corresponding optimal Joint 1, 2 and 3 positions by using the inverse kinematics process described in Section 6.2. This allows the use of interaction forces to move the exoskeleton shoulder mechanism while maintaining the optimal 4R configurations that were identified in Chapter 4.

7.4.1 Admittance control

When the exoskeleton behaves as an admittance, it moves in the direction of the user-generated force. This behavior is achieved by moving the target position of the upper arm in the direction of the force vector measured at the upper arm HRI. The magnitude of the measured force is used in the control gain to reduce the position error of each joint and move them to the new target position. Figure 7.13 shows an example of admittance control where force is applied at the upper arm HRI by a healthy human subject to move the upper arm in a circular path.

7.4.2 Impedance control

Impedance control for the 2 DOF shoulder movements is implemented using the same approach as that for the 1 DOF elbow. An artificial stiffness is used which allows the joints to deviate from their target positions according to the admittance controller output. Two examples of applying force during impedance control with a stationary upper arm target position are shown in Figures 7.14 and 7.15. In Figures 7.16 and 7.17, the impedance controller is applied to generate two different trajectories obtained from the smooth trajectory planner in Chapter 6.
Figure 7.13: An example of user-generated force applied in admittance control of the 2 DOF spherical shoulder. Force is applied at the upper arm HRI to move the upper arm in a circular path. The top plot shows the measured force vector with respect to the global coordinate system and the bottom plot shows the unit position of the upper arm relative to the ICOR.
Figure 7.14: An example of use-generated force applied in impedance control of the 2 DOF shoulder with a stationary target position. A force is applied at the upper arm HRI and then released. This is repeated for multiple arbitrary directions. The top plot shows the measured force vector with respect to the global coordinate system and the bottom plot shows the unit position of the upper arm relative to the ICOR.
Figure 7.15: An example of user-generated force applied in impedance control of the 2 DOF shoulder with a stationary target position. Force is applied at the upper arm HRI in a circular motion and then released. This is repeated multiple times. The top plot shows the measured force vector with respect to the global coordinate system and the bottom plot shows the unit position of the upper arm relative to the ICOR.
7.4 Control of the Redundant Shoulder Mechanism

Figure 7.16: An example of impedance control following a 90° shoulder flexion trajectory.
7.4 Control of the Redundant Shoulder Mechanism

Figure 7.17: An example of impedance control following a shoulder circumduction trajectory.
7.5 Chapter Summary

Two main control modes, admittance and impedance control, are developed to allow the 5 DOF exoskeleton prototype to interact with and respond to user-generated limb movements. In admittance mode, the position of the exoskeleton is unconstrained and the user can physically move the exoskeleton. Interaction force is measured by the force sensors at the HRI and used to drive the exoskeleton in the direction of the user-generated force. In this mode, the exoskeleton can generate either resistive or assistive forces in response to the user’s movement. Resistive forces are implemented in the form of an adjustable artificial damping and artificial inertia.

In impedance mode, the exoskeleton imposes position on the user’s limb by moving to a specified target position. This control mode is used to produce the trajectories generated by the smooth trajectory planner in Chapter 6. An adjustable artificial stiffness is used in this mode which allows the exoskeleton to deviate from its trajectory path when a force is applied by the user’s limb, thus achieving an artificial compliance effect. In addition, gravity and friction compensation algorithms are developed to make the user’s interaction with the exoskeleton feel light and seamless while operating in admittance and impedance modes.

User-generated movements of the shoulder are measured by a 2-axis force sensor to detect shoulder flexion & extension and abduction & adduction movements. However, directly using the force measurements to control the 4R joints is difficult since the 4R is a redundant mechanism and the relationship between shoulder and 4R movements is non-linear. To overcome this, the admittance and impedance controllers are developed to shift the target position of the upper arm according to the measured interaction force. This allows the 4R mechanism to maintain the optimal configuration for all target upper arm positions, thus ensuring the mechanism can feasibly move the upper arm in any direction at all times.

Experimental results are presented throughout this chapter to demonstrate various implementations of admittance and impedance control for both the elbow joint and shoulder joint. The exoskeleton produces the expected response in repeated experiments, even when the user-generated force is not the same.
Conclusions and Future Work

Current rehabilitation services utilize manual hands-on techniques and subjective evaluation methods with very limited use of technology. Rehabilitation services are unable to provide optimal treatment for patients due to the limitations of conventional methods. Insufficient availability of rehabilitation treatment, subjectivity and limited complexity of rehabilitation processes are major issues in conventional rehabilitation. Furthermore, there is growing demand for rehabilitation treatment due to the ageing population and thus increase in stroke patients. The use of exoskeleton robots for providing rehabilitation treatment is a promising solution to overcome the aforementioned issues.

It has been identified that the human shoulder joint is a particularly complex joint in the upper limb and recent exoskeletons designed for this joint are unable to achieve the same performance as the human counterpart. This research addresses the issues limiting exoskeleton shoulder movements and has produced a novel upper limb exoskeleton design that utilizes a smooth trajectory planning algorithm and force-based interactive control strategies. This chapter summarizes the conclusions drawn from the entire research work and proposes potential areas for future research.
8.1 Major Outcomes

The major outcome of this research was the development of a novel exoskeleton robot for upper limb rehabilitation. Through a comprehensive literature review and kinematic modeling of an upper limb exoskeleton, the major issues in the shoulder mechanism of past exoskeleton designs were revealed. The use of a novel 4R spherical wrist for the exoskeleton shoulder mechanism is proposed to overcome these limitations. However, the kinematic redundancy of the 4R mechanism allows for a range of possible designs which can all achieve the required workspace of the human shoulder joint. The 4R mechanism was analyzed to identify key performance criterions that can be used to evaluate a given design. These performance criterions were mathematically formulated and a multi-objective optimization algorithm was applied to obtain an optimal design. The optimized 4R mechanism design was then used in the development of a 5 DOF upper limb exoskeleton system capable of 3 DOF spherical motion of the shoulder joint and 1 DOF motion of the elbow joint, i.e. shoulder flexion & extension, abduction & adduction, medial & lateral rotation and elbow flexion & extension. Notable features of the exoskeleton design are its ability to reach the entire spherical shoulder workspace of a typical healthy adult and its user friendly design. The capability to achieve the entire spherical shoulder workspace gives physiotherapists the freedom to use all humanly possible spherical shoulder postures in rehabilitation processes. A trajectory planning algorithm was developed to derive trajectories for the exoskeleton joints which produce smooth movement of the human shoulder and elbow joints. A method to combine a sequence of movements into a single smooth trajectory was also implemented. Admittance and impedance controllers were developed to allow the exoskeleton to respond to user generated interaction forces and thus give the exoskeleton user a certain degree of control over the upper limb-exoskeleton system through limb movements. Further details on the above research outcomes are provided in the subsections below.

8.1.1 Analysis of spherical wrist mechanisms in shoulder exoskeletons

In order to determine the potential issues of using a spherical wrist mechanism for the shoulder complex of an exoskeleton robot, an analysis of the 3R mechanisms used in the majority of past exoskeleton designs was carried out. This investigation highlighted major problems associated with singularity and mechanical interference of the mechanism with the user which restrict the exoskeleton’s ability to operate in the shoulder workspace. These issues are caused by the exceptionally large range of motion of the human shoulder joint and
are particularly challenging to solve. Operating the mechanism at a singular configuration causes 1 DOF to be lost making the exoskeleton unable to generate shoulder rotations about the lost axis. Furthermore, the mechanism’s ability to rotate about this axis degrades as the mechanism approaches the singular configuration. Exoskeletons developed in the past that have considered singularity issues have only attempted to shift the singular configurations to regions of the workspace that are less commonly used by the shoulder and have not considered the reduction in performance near these configurations at all. For the exoskeleton designs with shifted singular configurations, analysis of mechanical interference between the exoskeleton and the user has revealed that parts of the 3R mechanism are required to operate dangerously close to the user’s body in order to reach some regions of the shoulder workspace. Exoskeleton designs that have not shifted the singular configuration cannot raise the upper arm above the horizontal position at all as this will cause the 3R mechanism to collide with the user. In order to overcome both the singularity and mechanical interference problems, the use of a redundant 4R spherical wrist mechanism is proposed for use in the shoulder complex of an exoskeleton robot.

8.1.2 Optimal 4R spherical wrist design for a shoulder exoskeleton

The proposed 4R spherical wrist mechanism is kinematically redundant and consequently a range of designs are possible which can achieve the entire shoulder workspace with adequate performance. In addition, the redundant 4R mechanism has infinite inverse kinematics solutions for achieving a given shoulder position. Thus, the NSGA II multi-objective optimization algorithm was used to identify an optimal 4R design and the optimal operating configurations of the mechanism. The variables defined in the optimization problem are used to determine the position of the base joint, the angle sizes of the three links in the 4R mechanism and the optimal operating configurations of the mechanism. The optimization objectives are formulated with considerations for reachable workspace, interference, singularity and joint transition feasibility throughout the workspace. Analysis of performance was done for 89 uniformly distributed upper arm positions in the semi-spherical shoulder workspace. The 4R mechanism’s ability to reach the entire shoulder workspace is guaranteed by the algorithm. Mechanical interference between the 4R mechanism and its components or the user was carefully analyzed and prevented. Singularity analysis was performed using the condition number of the mechanism’s configuration. To assess a 4R design’s singularity performance, the GCN was used to determine the average performance over the shoulder workspace and $\text{CN}_{\text{max}}$ was used to determine the closest the 4R mechanism
will operate to a singular configuration. The movements of the 4R mechanism’s joints were minimized to ensure they can transition feasibly and with minimal velocity throughout the shoulder workspace. An attempt was made to match the drift in the range of motion of the 4R mechanism joint that controls shoulder axial rotation to the drift in the range of motion of human shoulder axial rotation throughout the workspace.

The optimized 4R mechanism design obtained from the NSGA II algorithm has been analyzed and can feasibly achieve the compulsory requirements of reaching the entire semi-spherical shoulder workspace without mechanical interference. Comparisons between the performances of the optimized 4R design with other designs confirm the improved performance of this mechanism in a shoulder exoskeleton.

**8.1.3 5 DOF active upper limb exoskeleton system**

The optimized 4R spherical wrist mechanism has been used in the design of a 5 DOF upper limb exoskeleton system. This exoskeleton is capable of performing 3 DOF spherical movements of the shoulder joint and 1 DOF movement of the elbow joint through the entire range of motion of a healthy adult's limb. Numerous considerations were made to ensure the exoskeleton design can achieve the required range of motion with adequate performance, is feasible to develop with the available resources and is user-friendly. These considerations include size, weight, range of motion, velocity, torque, mechanical interference, cost, fabrication time, joint alignment, customization for different users, options for future upgrades, ease of use, safety and noise pollution. The exoskeleton is supported by a mechanically grounded frame behind the user so that the user does not carry the weight of the exoskeleton but is instead supported by it. Length adjustments can be made to the exoskeleton structure to fit users with different arm lengths. The exoskeleton joint that controls shoulder axial rotation is implemented using a 120° curved rail encompassing the side of the upper arm which makes the exoskeleton easy to don and prevents mechanical interference issues. Each of the five joints in the exoskeleton is actuated by a compact brushless DC motor in combination with a reduction gearbox directly mounted onto the joints. Position feedback for the five exoskeleton joints is provided by rotary magnetic encoders and force feedback is achieved using low-cost custom-built strain gauge force sensors at the hand and upper arm HRI. Numerous safety features are incorporated into the exoskeleton including mechanical stoppers to physically prevent the joints from extending beyond their standard range of motion, software to monitor the joint positions via the magnetic encoders and prevent the motor from driving the joint beyond the range of motion.
limits, and emergency stop buttons to allow the exoskeleton user or an external user to manually stop the exoskeleton. Simulations confirm the complete exoskeleton system does not have mechanical interference issues when operating within the human workspace. A GUI has been developed for operating the exoskeleton robot.

8.1.4 Smooth trajectory planner

In controlling the position of an exoskeleton, it is important to consider the velocities the joints move with in travelling to a target position to ensure the movement is smooth, comfortable and similar to normal human motion. It has been identified that typical human movements follow a minimum jerk trajectory where the rate of change in acceleration (jerk) is minimized throughout the trajectory. A trajectory planning algorithm based on the minimum jerk criterion has been developed for the joints present in the 5 DOF upper limb exoskeleton. This requires an input of the target positions for the joints and the desired time for the joints to arrive at those positions. Implementation of this is fairly straightforward for the 1 DOF elbow joint since the movements of the exoskeleton joint translate directly to identical movements in the user’s elbow joint. However, movements of the joints in the exoskeleton’s spherical wrist shoulder mechanism have a non-linear relationship with the movements of the user’s shoulder joint. In other words, a minimum jerk trajectory of the joints in the 4R mechanism does not generate a minimum jerk trajectory for the user’s shoulder. Therefore, the minimum jerk trajectory is firstly determined for the shoulder movement which is then converted to the respective trajectories of the 4R joints.

As previously stated, there are infinite inverse kinematics solutions due to the kinematic redundancy of the 4R mechanism. To obtain a unique inverse kinematics solution, a set of optimal operating configurations for 89 upper arm positions obtained during design optimization is used. For an arbitrary target upper arm position, the optimal joint configuration is determined by interpolating the 89 known optimal configurations.

A method for combining a series of point-to-point movements into a single smooth trajectory has also been developed, enabling the implementation of complex movements and task-based exercises. Changes in velocity along a trajectory path, temporarily remaining in a stationary position, reversals in movement direction and turning in shoulder movements can all be achieved by setting a sequence of target positions and the target times for reaching these positions.
8.1.5 Force-based interactive control strategies

Admittance and impedance control strategies have been implemented in the upper limb exoskeleton to allow it to interact and respond to movements generated by the user. A dynamic model of the system is developed with considerations for inertial, frictional and gravitational forces. Admittance control allows the user to assume control of movement such that the exoskeleton moves when pushed by the user’s limb, enabling the exoskeleton to provide assistance or resistance to the user’s movements. The impedance controller is used to impose a position for the user’s limb with an adjustable artificial stiffness behavior. A reduced stiffness allows user-generated forces to have a larger influence on the exoskeleton’s position. Trajectory tracking can be implemented with an artificial stiffness to allow the exoskeleton to deviate from the trajectory path when a force is applied by the user’s limb and thus producing an artificial compliance effect.

These types of responses to user-generated forces can be used in various rehabilitation applications. The difficulty level of rehabilitation exercises can be adjusted to suit users with different levels of disability by changing the amount of assistance or resistance provided by the exoskeleton.

8.2 Future Work

This research has produced an upper limb exoskeleton with the core functionalities implemented. Although the desired exoskeleton functions have been achieved, improvements can be made and new capabilities can be developed for the present exoskeleton system.

8.2.1 Improve components of existing system

The present exoskeleton is the first generation prototype and much of the exoskeleton system was developed using components that were chosen because of their low cost or short development time rather than their suitability for an upper limb rehabilitation exoskeleton. The current exoskeleton structure is constructed almost entirely from aluminium plates which were fabricated by water jet cutting. Due to the limitations in the shapes of structural members that can be constructed using only plates, the size of these structural members are larger in size than is necessary. The member shapes are also not specifically designed to support the loads they are required to carry so twisting and bending of the exoskeleton structure occurs. Furthermore, aluminium has a poor strength to weight ratio compared to
composite materials. The use of better designed structural members using a stronger material can reduce the size and weight of the current exoskeleton system and improve its rigidity.

In addition, the gearboxes used in the exoskeleton system are large and heavy. Four of the five current gearboxes use multi-stage reduction planetary gears which occupy a large amount of space. The size and weight of the gearbox can be reduced significantly if harmonic drives [118] are used instead. Designing a custom actuator specifically for the exoskeleton may also reduce the size and weight of the system.

### 8.2.2 Higher DOF exoskeleton

The current exoskeleton system is capable of moving the shoulder spherically in 3 DOF and the elbow in 1 DOF flexion & extension movement. It was identified in Chapter 3 that the upper limb has 9 DOF from the shoulder to the wrist. The 5 missing DOF are at the top and bottom ends of the exoskeleton’s serial manipulator. The top is missing 2 DOF for shoulder translations whereas the bottom is missing 3 DOF for spherical rotation of the wrist joint. Implementation of shoulder translations will require an effective interface that can apply forces directly to the user’s shoulder. The addition of a mechanism for the wrist joint will increase the mass of the exoskeleton therefore the power of existing actuators will need to be taken into consideration.

The most beneficial upper limb movements to implement next are the 3 DOF spherical movements of the wrist joint as these movements pay an important role in functional tasks. Since the spherical range of motion of the human wrist joint is significantly smaller than that of the shoulder, a 3R mechanism can be used for the wrist without singularity or interference issues.

### 8.2.3 Human-robot interfaces

In the current exoskeleton system, the only interaction between the exoskeleton and its user is the mechanical force at the hand and upper arm. These interfaces were made using plastic parts from a 3D printer with little consideration for the user’s comfort. They should have an ergonomic design and use a material that is comfortable for the user to touch. Additionally, the ideal locations on the surface of the user’s upper limb for transferring mechanical forces should also be studied. Mechanical interfaces in regions with a high pain tolerance can improve the user’s safety and comfort while attachments on stable body structures with low compliance improves load transfer between the exoskeleton and the human limb.
Apart from HRI for force transfer, other methods of interaction between the exoskeleton and its user can be used to increase the exoskeleton’s capabilities. The exoskeleton can communicate with the user using haptic vibrations on the user’s skin. Functional electrical stimulation can be used to electrically activate the user’s muscles during rehabilitation exercises. Conversely, electrodes can be used to measure EMG signals from the user’s muscles to determine the user’s movement intent. The locations for these HRI will also need to be carefully considered to ensure effective interaction.

### 8.2.4 Task-based exercises

The human upper limb requires coordination and precise control for manipulation tasks as opposed to the lower limb which requires strength to support the body’s weight. Therefore, the rehabilitation exercises for the upper limb should be designed to work on the joints’ precision and control with a task-oriented approach. The ability to implement task-based exercises is an important feature of exoskeletons as these exercises are difficult to implement with conventional rehabilitation techniques that are based on hands-on methods. Exoskeletons are capable of accurately controlling multiple joints simultaneously, enabling them to produce realistic task-based exercises for the patient. The difficulty of the exercises can also be adjusted to suit different levels of disability. Task-based exercises can be incorporated into virtual games to provide a more enjoyable rehabilitation experience and thus motivating the patient to put more effort into the exercises. This will in turn accelerate the patient’s rate of recovery.

In this research, the tools to implement various types of exercises have been developed in the form of the smooth trajectory planner, admittance controller and impedance controller but specific exercises have yet to be formulated. The exercises should be developed through collaboration with physiotherapists to create highly effective exercises.

In the future, this concept can potentially be extended to teach healthy individuals more sophisticated movements such as those in occupational tasks or sports, e.g. the arm movements in badminton. In the entertainment sector, exoskeletons can provide a more interactive gaming experience in which the movement of the player’s arm can be mimicked by the arm of a game character and the physical interactions of the game character can be felt by the player through the exoskeleton. Evidently, research of exoskeletons for rehabilitation has synergies with many other fields and exoskeleton use can branch to diverse application areas. These examples provide a glimpse of the vast potential of exoskeleton technology.
8.3 Summary

The tools and algorithms developed throughout this research have helped to address several key limitations and requirements in realizing an exoskeleton robot for upper limb rehabilitation. The shoulder and elbow mechanisms in the exoskeleton prototype can achieve the same range of motion and movements as that of a typical healthy adult. Fundamental algorithms for smooth trajectory planning and force-based interactive control have been developed and can be used to implement sophisticated rehabilitation processes. The tools developed in this work can provide valuable improvements to rehabilitation services which benefits both patients and physiotherapists.

8.2.5 Disability evaluation

Assessing disability of the upper limb is a complex task and numerous measures of stroke severity and functional ability have been proposed in the past. These disability measures often utilize a scoring system which is performed using subjective methods. Examples include the Barthel Index (BI) for measuring a patient’s performance in activities of daily life [119] and the Fugl-Meyer (FM) assessment for measuring patient recovery [120]. These assessments are performed by having the physiotherapist give a score to indicate how well a patient performs a movement or task. However, the information obtained from these subjective methods only provides a rough impression of the patient’s disability and cannot be reliably used to compare between results [121].

An exoskeleton can make live quantitative measures of patient-generated effects such as interaction force and EMG signals. This information can be used to obtain a detailed objective evaluation of individual joints and muscle groups in the patient’s limb. A detailed disability assessment can improve identification of the patient’s problems, allow treatment intervention to be optimized according to the patient’s condition, allow reliable comparison between disability assessment results and improve the quality of rehabilitation research. Objective evaluations of disability have largely been left unexplored due to the lack of suitable tools and there are currently no protocols available for exoskeleton-based evaluations. New guidelines will need to be developed through collaboration with physiotherapists to create a new protocol for objective evaluations that utilize the new exoskeleton tools. Objective evaluations will make rehabilitation studies more reliable which in turn will allow mankind to gain a better understanding of the human neuromuscular system and determine the optimal rehabilitation treatment for different disability conditions.
Appendix: Optimal 4R Mechanism Configurations

Optimal 4R mechanism configurations were obtained for reaching 89 uniformly separated upper arm positions in the workspace during the optimization process in Chapter 4. The 89 optimal configurations for the left shoulder are presented in this appendix.

Figure A.1: The 89 uniformly separated points in the workspace of the left shoulder.
Figure A.2: Numbers assigned to the 89 workspace points. The red points are not used in the GUI for operating the exoskeleton as they are considered dangerous for the user.

Figure A.3: Default configuration of the 5 DOF exoskeleton.
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Figure A.4: Optimal 4R configurations for shoulder workspace points 1 to 6.
Figure A.5: Optimal 4R configurations for shoulder workspace points 7 to 12.
Figure A.6: Optimal 4R configurations for shoulder workspace points 13 to 18.
Figure A.7: Optimal 4R configurations for shoulder workspace points 19 to 24.
Figure A.8: Optimal 4R configurations for shoulder workspace points 25 to 30.
Figure A.9: Optimal 4R configurations for shoulder workspace points 31 to 36.
Figure A.10: Optimal 4R configurations for shoulder workspace points 37 to 42.
Figure A.11: Optimal 4R configurations for shoulder workspace points 43 to 48.
Figure A.12: Optimal 4R configurations for shoulder workspace points 49 to 54.
Figure A.13: Optimal 4R configurations for shoulder workspace points 55 to 60.
Figure A.14: Optimal 4R configurations for shoulder workspace points 61 to 66.
Figure A.15: Optimal 4R configurations for shoulder workspace points 67 to 72.
Figure A.16: Optimal 4R configurations for shoulder workspace points 73 to 78.
Figure A.17: Optimal 4R configurations for shoulder workspace points 79 to 84.
Figure A.18: Optimal 4R configurations for shoulder workspace points 85 to 89.
B.1 Motor Requirements

In the selection of a specific motor actuator for each of the five joints in the upper limb exoskeleton, multiple factors are considered including performance, range of motion, weight, size, back-drivability and cost. The performance requirements are torque and velocity which are approximated by considering slightly extreme scenarios of human upper limb movement.

The assumed velocity requirement for the shoulder and elbow joints are half a revolution per second or 30 rpm which is reasonably fast compared to movements in performing common tasks. This velocity requirement of 30 rpm is assumed for Joints 1, 2 and 5 for simplicity. The actual velocity requirements of Joints 1 and 2 in the 4R mechanism will be similar to this value for a shoulder rotation velocity of 30 rpm since the 4R mechanism is optimized to operate far away from singular configurations (see Chapter 4). Due to the smaller range of motion of Joints 3 and 4, the velocity requirement for these two joints is approximated as 20 rpm.

The torque requirement considers the weight which the joint needs to support as well as the potential torque applied by the user’s limb. The torques caused by inertia, Coriolis and centrifugal effects are small since the exoskeleton operates at low accelerations and velocities.
and therefore are not considered in the torque requirement calculations. Firstly, the joint torque caused by the weight of the exoskeleton components and the user’s upper limb are considered. Since the weight of the exoskeleton-upper limb system shifts during operation, simulation of a 3D CAD model of the exoskeleton in Creo Parametric is used to estimate the maximum torques that occurs for each joint. These occur when the upper limb is lifted into a straight horizontal position. Next, the user-generated torque is approximated by applying a 25 N force at the hand position of the horizontally positioned limb. The load torque caused by the weight of motors and gearboxes chosen for distal joints are also considered in the calculation. Therefore, the approximation of actuator requirements is done in tandem with the selection of the motors and gearboxes. The approximated requirements of joint velocity and torque are provided in Table B.1.

Note that the estimated torque requirement of Joint 1 is smaller than all the other joints even though it is supporting more components. This is because the axis of rotation of Joint 1 is constantly tilted resulting in a reduced component of gravitational torque acting about the joint axis. In addition, the majority of the exoskeleton mass is near the vertical plane intersecting the axis of Joint 1 during operation therefore the horizontal perpendicular distance to the center of mass is small (Figure B.1). Joint 2 has a large estimated torque requirement because the axis of rotation of Joint 2 can enter a near horizontal position during operation which maximizes the load carried by the joint. Furthermore, the exoskeleton structures supported by Joint 2 tend towards one side of the joint axis (Figure B.2). This also applies to Joint 3 which also has a relatively large torque requirement.

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Figure B.1: The moment acting about Joint 1 axis due to gravitational forces is relatively small due to the large angle between the Joint 1 axis and the horizontal plane and the short perpendicular distance to the weight of the system.
Figure B.2: The moment acting about Joint 2 axis due to gravitational forces is relatively large due to the small angle between the Joint 2 axis and the horizontal plane and the large perpendicular distance to the weight of the system.
The torque and velocity output of a motor are inversely proportional therefore the actuator requirements in Table B.1 refers to the exertion of torque while operating at the specified velocity. A motor can exert a larger torque than the nominal torque if it is running slower than the nominal velocity and can run at a higher velocity than the nominal velocity if the exerted torque is lower. The exoskeleton is not expected to operate the motors at both the required torque and velocity simultaneously. Therefore, the torque and velocity requirements are an overestimation and are only used as a guideline during motor selection. The weight and especially size or the motors are also important to ensure the motors can fit in the limited space in the exoskeleton structure.

### B.2 Motor Selection

The motors chosen to actuate each of the five exoskeleton joints are Maxon 24V brushless DC motors in combination with reduction gearboxes (Maxon Motor, Switzerland) [122]. These motors are back-drivable and have a special flat design which allows them to be mounted directly at the exoskeleton joints without causing interference problems. Maxon ESCON controllers are used to drive each motor.

The motor-gearbox combinations are carefully selected for each joint (see Table B.2) to ensure the required output torque and velocity specified in Table B.1 can be achieved. Due to the high torque and low speed requirement of the exoskeleton joints, a high reduction ratio is required from the gearboxes. The gearboxes used for Joints 1, 2, 3 and 5 are planetary gearboxes with three stages of reduction for Joints 1, 2 and 5 and four stages of reduction for Joint 3. A spur gearbox with three stage reduction is used for Joint 4.

<table>
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*Values after a further reduction of 6:1 by the Joint 4 rail mechanism.
In addition, the weight and size of each motor-gearbox unit is also considered in conjunction with the structural design of the exoskeleton to ensure they can be mounted directly at the exoskeleton joints without interfering with the movements of the exoskeleton. Interference analysis is done by simulating a 3D CAD model of the exoskeleton system in Creo Parametric. In particular, extra attention was made in selecting the motor-gearbox units and designing the exoskeleton structure for Joints 3 and 4 since attaching the motor-gearbox unit onto these joints are the most likely to cause interference. A motor-gearbox unit on Joint 3 can interfere with Link 1 (the link between Joint 1 and Joint 2) when it overlaps with Link 2 (the link between Joint 2 and Joint 3) as shown in Figure B.3a. The structure of Links 1 and 2 are carefully designed to ensure this interference does not occur. In the case for Joint 4, there is very limited space available for the Joint 4 motor-gearbox unit since the motor-gearbox unit of Joint 5 is mounted nearby (Figure B.3b). Therefore, a smaller-sized spur gearbox is selected to combine with the motor of Joint 4 instead of the larger planetary gearbox used for the other motors. The spur gearbox is available in a limited reduction ratio but this is not an issue for Joint 4 since the curved rail mechanism in this joint applies a further reduction of 6:1.

The nominal output torques and velocities of the chosen motor-gearbox units in Table B.2 are all similar or better than the approximated requirements in Table B.1. The motor-gearbox unit for Joint 3 has the largest under-performance when compared to the proposed requirements. Although a larger motor-gearbox unit would improve the performance for Joint 3, the weight of the motor-gearbox unit will increase which means the motors of Joints 1 and 2 will also need to be more powerful. Furthermore, since the motor-gearbox unit of Joint 3 can interfere with Link 1 as discussed earlier, a larger motor will require the link designs to be modified in a way which will further increase the load on Joints 1 and 2. Also, the nominal output torque and velocity is the maximum output when the joint is generating both the torque and velocity output simultaneously. This will rarely occur in the exoskeleton since its usage will often involve low velocities when a high load is applied or vice versa. The chosen motor-gearbox combination for Joint 3 is the best compromised solution after considering all the trade-offs.
Figure B.3: Potential occurrences of mechanical interference (a) between Joint 3 motor and Link 1 and (b) between Joint 4 motor and Joint 5.
B.3 Sensors

Sensors are incorporated into the exoskeleton design to measure the rotary position of the five joints and the interaction forces between the user’s limb and the exoskeleton structure.

Angular position encoders pre-installed onto the motors are available and is a convenient option however this makes it not possible to measure the angular displacement of the gearbox output shaft without knowledge of its position when the system starts up. Instead, absolute encoders are installed onto the exoskeleton joint to measure the angular displacement of the joint directly. This is achieved using AMS magnetic rotary encoders (AMS, Austria) [123]. These are high resolution absolute encoders which measures a displacement angle relative to a pre-programmed zero position. The encoder operates by measuring the direction of the magnetic field near a permanently magnetized metal disc.

Force measurement is achieved using custom-made force sensors comprising of RS strain gauges [124] attached to a specially designed aluminium load structure. This is a low-cost alternative to the otherwise very expensive commercial force sensors. Each axis of force measurement uses a pair of strain gauges, one on each side of the load structure (Figure B.5). A force applied to the end of the load structure causes it to bend resulting in compression of one strain gauge and extension of the other. This results in an increase in electrical resistance of the strain gauge under extension and a decrease in resistance for the strain gauge under compression. The use of a pair of strain gauges instead of one increases the sensitivity and compensates for changes in resistance due to temperature. The load structure is designed so that the strain gauges deform only when force is applied in the axis it is measuring and experience negligible deformation from force applied orthogonal to this axis.

The pair of strain gauges is incorporated in a Wheatstone bridge circuit in half-bridge configuration (Figure B.4). This circuit uses the change in resistance to generate an output voltage difference. This voltage difference is then amplified using an instrumentation amplifier and is converted to a noise-resistant digital signal using an I2C analog-to-digital converter (ADC).
Appendix: Actuators and Sensors

Figure B.4: A pair of strain gauges in a Wheatstone bridge in half-bridge configuration used in the force sensor.

Figure B.5: Force sensing method. (a) Load specimen with no force applied. The Wheatstone bridge is balanced and the output voltage is zero. (b) Load specimen with force applied. The Wheatstone bridge is unbalanced and the output voltage is a function of the applied force.
Appendix: Human Participants Ethics Application

Reference Number 2011 / _146_

University of Auckland Human Participants Ethics Committee (UAHPEC)

RESEARCH PROJECT APPLICATION FORM (2010)

DECLARATION FOR ALL SIGNATORIES:
The information supplied is, to the best of my knowledge and belief, accurate. I have read the current Guiding Principles and Applicants’ Manual 2010. I clearly understand the obligations and the rights of the participants, particularly in regard to obtaining freely given informed consent. I confirm that the Application Checklist is completed adequately and attached to this application.

SUPERVISOR:

<table>
<thead>
<tr>
<th>Name</th>
<th>Shane Xie</th>
</tr>
</thead>
<tbody>
<tr>
<td>Postal address</td>
<td></td>
</tr>
<tr>
<td>Email address</td>
<td><a href="mailto:s.xie@auckland.ac.nz">s.xie@auckland.ac.nz</a></td>
</tr>
<tr>
<td>Phone number</td>
<td>+64 (9) 3737599 ext. 88143</td>
</tr>
<tr>
<td>Department</td>
<td>Mechanical Engineering</td>
</tr>
</tbody>
</table>

Signature Date

186
**STUDENT (This includes Doctoral, Masters and Honours student):** (If applicable)

<table>
<thead>
<tr>
<th>Name</th>
<th>Ho Shing Lo</th>
</tr>
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<tbody>
<tr>
<td>Postal address</td>
<td></td>
</tr>
<tr>
<td>Email address</td>
<td><a href="mailto:hlo015@aucklanduni.ac.nz">hlo015@aucklanduni.ac.nz</a></td>
</tr>
<tr>
<td>Phone number</td>
<td></td>
</tr>
<tr>
<td>Department</td>
<td>Mechanical Engineering</td>
</tr>
<tr>
<td>Name of degree</td>
<td>Doctor of Philosophy</td>
</tr>
</tbody>
</table>

**Signature**

**Date**

**OTHER INVESTIGATORS:** (If applicable)

<table>
<thead>
<tr>
<th>Names</th>
<th></th>
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<tbody>
<tr>
<td>Organisation</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Is ethical approval being applied for from another institution?</th>
<th>YES</th>
<th>NO</th>
</tr>
</thead>
</table>

**AUTHORIZING SIGNATURES**

<table>
<thead>
<tr>
<th>Name of Head of Department or Nominee</th>
<th>Gordon Mallinson</th>
</tr>
</thead>
<tbody>
<tr>
<td>Email address</td>
<td><a href="mailto:g.mallinson@auckland.ac.nz">g.mallinson@auckland.ac.nz</a></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signature of Head of Department or Nominee</th>
<th>Date</th>
</tr>
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</table>

**This is only required if the answer to section F is “Yes”**.

<table>
<thead>
<tr>
<th>Name of Pro Vice Chancellor (Māori) / Nominee</th>
<th></th>
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<tr>
<td>Email address</td>
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</table>

<table>
<thead>
<tr>
<th>Signature of Pro Vice Chancellor (Māori) / Nominee</th>
<th>Date</th>
</tr>
</thead>
</table>
### APPLICATION CHECKLIST (Please delete whichever is not applicable)

#### General Information
- Is the application form dated for the current year? (Any application not using the current form on the website will be returned.)  **YES**
- Have you obtained all the signatures on pages 2 and 3 (wherever applicable)?  **YES**
- Have you addressed the ethical issues on A4? (Please note that "Not applicable" is not acceptable. The Committee will not consider the application if this is not answered adequately.)  **YES**
- Have you completed all sections?  **YES**
- Have you attached the advertisement?  
- Have you attached the questionnaire?  
- Have you attached the list of interview questions?  
- Have you attached the transcriber confidentiality agreement? (Please refer to the Applicants' Manual Section 5c for sample format.)  
- Have you consulted an ethics advisor in preparing the application? If yes, please provide the name and email address.
  - Name of ethics advisor: ________ Dr Ashvin Thambyah
  - Email: ___________ ashvin.thambyah@auckland.ac.nz  **YES**

#### Preliminary Assessment

### A. Risk of Harm

1. Does the research involve situations in which the researcher may be at risk of harm?  **YES**
2. Does the research involve the use of any method, whether anonymous or not, which might reasonably be expected to cause discomfort, pain, embarrassment, psychological or spiritual harm to the participants?  **NO**
3. Does the research involve processes that are potentially disadvantageous to a person or group, such as the collection of information which may expose the person/group to discrimination?  **NO**
4. Does the research involve collection of information about illegal behaviour(s) which could place the researcher or participants at risk of criminal or civil liability or be damaging to their financial standing, employability, professional or personal relationships?  **NO**
5. Does the research involve any form of physically invasive procedure on participants, such as the collection of blood, body fluids, tissue samples, DNA, human tissue from a tissue bank, exercise or dietary regimes or physical examination?  **NO**
6. Does the research involve any intervention administered to the participant, such as drugs, medicine (other than in the course of standard medical procedure), placebo, environmental conditions, food/drink?  **NO**
7. Does the research involve processes that involve EEG, ECG, MRI, TMS, FMRI, EMG, radiation, invasive or surface recordings?  **YES**
8. Is the research considered a clinical trial?  **NO**
9. Does the research involve physical pain beyond mild discomfort?  **NO**

### B. Informed and Voluntary Consent

1. Does the research involve participants giving oral consent rather than written consent? (If participants are anonymous the response is "No").  **NO**
2. Does the research involve participation of children (seven years old or younger)?  **NO**
3. Does the research involve participation of children under sixteen years of age where parental consent is not being sought?  **NO**
4. Does the research involve participants who are in a dependent situation, such as people with a disability, residents of a hospital, nursing home or prison, or patients highly dependent on medical care?  **NO**
5. Does the research involve participants who are being asked to comment on employers?  **NO**
6. Does the research involve participants (other than children) whose capacity to give informed consent is in doubt?  **NO**
<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>7. Does the research use previously collected information or biological samples for which there was no explicit consent?</td>
<td>NO</td>
</tr>
<tr>
<td><strong>C. Research conducted overseas</strong></td>
<td></td>
</tr>
<tr>
<td>1. Will the research be conducted overseas?</td>
<td>NO</td>
</tr>
<tr>
<td><strong>D. Privacy and confidentiality issues</strong></td>
<td></td>
</tr>
<tr>
<td>1. Does the research involve evaluation of University of Auckland services or organisational practices where information of a personal nature may be collected and where participants may be identified?</td>
<td>NO</td>
</tr>
<tr>
<td>2. Does the research involve University of Auckland staff or students where information of a personal nature may be collected and where participants may be identified?</td>
<td>NO</td>
</tr>
<tr>
<td>3. Does the research involve matters of commercial sensitivity?</td>
<td>NO</td>
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<tr>
<td>4. Does the research involve Focus Groups?</td>
<td>NO</td>
</tr>
<tr>
<td><strong>E. Deception</strong></td>
<td></td>
</tr>
<tr>
<td>1. Does the research involve deception of the participants, including concealment or covert observations?</td>
<td>NO</td>
</tr>
<tr>
<td><strong>F. Conflict of interest</strong></td>
<td></td>
</tr>
<tr>
<td>1. Does the research involve a conflict of interest or the appearance of a conflict of interest for the researcher (for example, where the researcher is also the lecturer/teacher/treatment provider/colleague or employer of the participants, or where there is a power relationship between researcher and participants)?</td>
<td>NO</td>
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<tr>
<td><strong>G. Cultural sensitivity</strong></td>
<td></td>
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<tr>
<td>1. Does the research have impact on Maori?</td>
<td>NO</td>
</tr>
<tr>
<td>2. Does the research raise any specific ethnic or cultural issues not relating to Maori?</td>
<td>NO</td>
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<tr>
<td><strong>H. Requirements imposed from outside The University of Auckland</strong></td>
<td></td>
</tr>
<tr>
<td>1. Does the research involve a requirement imposed by an organisation outside The University of Auckland?</td>
<td>NO</td>
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</tbody>
</table>
### Have you included the following information in the Participant Information Sheet? (Please note that this is not an exhaustive list. Please refer to the Applicants' Manual Sections 2c and 5a for more information.)

<table>
<thead>
<tr>
<th>Information</th>
<th>Included</th>
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<tbody>
<tr>
<td>On University of Auckland Departmental letterhead</td>
<td></td>
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<tr>
<td>Project title</td>
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<tr>
<td>Researcher name</td>
<td></td>
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<tr>
<td>Position of staff and /or Degree of the student</td>
<td></td>
</tr>
<tr>
<td>Address by category, e.g. Participant Information Sheet for Manager</td>
<td></td>
</tr>
<tr>
<td>Explain the project in simple language</td>
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<tr>
<td>Actual date/period for withdrawal of data</td>
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<tr>
<td>Length of time involvement</td>
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<tr>
<td>Source of funding</td>
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<tr>
<td>State whether audio/videotaping</td>
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<tr>
<td>Data storage/retention/destruction/future use</td>
<td></td>
</tr>
<tr>
<td>Confidentiality statement</td>
<td></td>
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<tr>
<td>Participation/non-participation statement</td>
<td></td>
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<tr>
<td>(Please refer to the Applicants’ Manual Section 2c iv)</td>
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<tr>
<td>Contact details (This includes the details of the researcher, supervisor, HOD and Chair)</td>
<td></td>
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<tr>
<td>Approval wording</td>
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</table>

### Have you included the following information in the Consent Form? (Please note that this is not an exhaustive list. Please refer to the Applicants’ Manual Sections 2d and 5b for more information.)

<table>
<thead>
<tr>
<th>Information</th>
<th>Included</th>
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<tbody>
<tr>
<td>On University of Auckland Departmental letterhead</td>
<td>YES</td>
</tr>
<tr>
<td>Project title</td>
<td>YES</td>
</tr>
<tr>
<td>Researcher name</td>
<td>YES</td>
</tr>
<tr>
<td>Address by category, e.g. Consent Form from Manager</td>
<td>YES</td>
</tr>
<tr>
<td>Actual date/period for withdrawal of data</td>
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</tr>
<tr>
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<td>Data storage/retention/destruction/future use</td>
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</tr>
<tr>
<td>Confidentiality statement</td>
<td>YES</td>
</tr>
<tr>
<td>Participation/non-participation statement</td>
<td>YES</td>
</tr>
<tr>
<td>Participant’s and / or legal guardian’s name, signature and date</td>
<td>YES</td>
</tr>
<tr>
<td>Approval wording</td>
<td>YES</td>
</tr>
</tbody>
</table>
SECTION A:

1. **Project title**

   Development of a Wearable Exoskeleton Robot for Upper Limb Rehabilitation and Power Assist

2. **Aims/objectives of project**
   (Describe in plain language that is comprehensible to lay people and free from jargon.)

   Development of a wearable robotic device for the human arm. The purpose of the robotic device is to provide rehabilitation exercises and to assist movements of the arm.

3. **Research background**
   (Provide sufficient information to place the project in perspective and to allow the significance of the project to be assessed.)

   Rehabilitation from stroke is a long and labour intensive process. Current rehabilitation services are struggling to provide adequate treatment to patients. Robotic therapy is a possible solution. Exoskeleton robots have the advantage of being able to provide intensive rehabilitation consistently for a long duration and irrespective of the skills and fatigue level of the physiotherapist. Exoskeletons are also able to treat the patient without the presence of the therapist, enabling more frequent treatment and reducing costs. In addition, exoskeletons can accurately measure quantitative data to evaluate the patient’s condition. Exoskeletons can potentially open up new areas of research such as the development of new rehabilitation methods.

4. **Identify the ethical issues arising from this project and explain how they can be resolved.**
   (For example: confidentiality, anonymity, informed consent, participant’s rights to withdraw, conflict of interest, etc.)
   (UAHPEC expects applicants to identify the ethical issues in the project and explain in the documentation how they have been resolved. The application will not be considered if this is not answered adequately. A "Not applicable" response is not acceptable.)

   Safety is the main ethical issue in this project. The robotic device is in direct contact with the human arm and may harm the user if a malfunction occurs. For details on the potential causes of injury and safety measures that will be implemented, refer to the Risk Management Plan.

SECTION B:

1. **Who are the participants in the research?**
   (Delete those who do not apply)

   | Other – Researcher (Myself) |

2. **Explain how many organisations, departments within the organisations, and individuals you wish to recruit.**
   (Attach any letter of support you may have had from an organisation.)

   | 1 (myself) |
3. **How will you obtain the names and contacts of participants?**
   (If by advertisement or email, attach a copy to the application. If through an agency holding these details, attach a copy of support letter.)

   N/A (researcher is participant)

4. **Who will make the initial approach to potential participants?**
   (For example: will the owner of the database send out letters?)

   N/A (researcher is participant)

5. **Is there any special relationship between participants and researchers?**

   NO

6. **Are there any potential participants who will be excluded?**

   NO

**SECTION C: RESEARCH PROCEDURES**

1. **Project duration** (Dates during which data needs to be collected for this study and requires ethics approval.)

   From 1/08/2011 to 31/04/2014

2. **Describe the study design.**
   (For example: If it is a longitudinal study, explain what a longitudinal study is and provide the details.)

   The research involves the development and testing of a wearable robotic device for the human arm. The device will be tested on the researcher (Ho Shing Lo). Experiments will be performed with the device attached to the researcher’s arm. These tests will involve the researcher voluntarily moving his arm, the robot moving the researcher’s arm, and a combination of both. All movements will be within the range of motion of the human joints and at velocities lower than that achievable by the human joints. The data collected from these tests will be used to verify a biomechanical model of the arm and to assist in developing a method to automatically calibrate the device to the user.

3. **List all the methods used for obtaining information.**
   (Delete those that do not apply)

   N/A

4. **Who will carry out the research procedures?**

   Ho Shing Lo (myself)
5. a) Where will the research procedures take place?  
(Physical location/setting)  
**University of Auckland, Engineering Building, Mechatronics Lab**

b) If the study is based overseas, which countries are involved?  
(Provide local contact information on the PIS.)  
**N/A**

c) If the study is based overseas, explain what special circumstances arise and how they will be dealt with? Explain if there are any special requirements of the country (e.g. research visa) and/or the community with which the research will be carried out?  
**N/A**

6. If the questionnaire is web-based, explain how anonymity can be preserved.  
(Indicate this on the PIS.)  
**N/A**

7. How much time will participants need to give to the research?  
(Indicate this on the PIS.)  
**3 years**

8. Will information on the participants be obtained from third parties?  
**NO**

9. Will any identifiable information on the participants be given to third parties?  
**NO**

10. Are you intending to conduct the research in University of Auckland class time?  
**NO**

11. Is deception involved at any stage of the research?  
**NO**

12. Is there any koha, compensation or reimbursement of expenses to be made to participants?  
**NO**
13. a) Does the research involve the administration of any substance to participants? 

[ ] NO

b) Does this research involve potentially hazardous substances? 

[ ] NO

SECTION D: INFORMATION AND CONSENT

1. By whom and how will information about the research be given to participants? 
(For example: in writing or verbally – a copy of information to be given to prospective participants in the form of a PIS must be attached to this application.) 

N/A (researcher is the participant)

2. a) Will the participants have difficulty giving informed consent on their own behalf? 
(Consider physical or mental condition, age, language, legal status, or other barriers.) 

[ ] NO

b) If participants are not competent to give fully informed consent, who will consent on their behalf? 
(For example: parents/guardians)

[ ]

3. a) If a questionnaire is used, will the participants have difficulty completing the questionnaire on their own behalf? 
(Consider physical or mental condition, age, language, legal status, or other barriers.) 

[ ] NO

b) If participants are not competent to complete the questionnaire, who will act on their behalf? 
(For example: parents/guardians) 

N/A

4. Is informed consent obtained in writing? 

[ ] YES
5. Is access to the Consent Forms restricted to the Principal Investigator and/or the researcher?

YES

6. Will Consent Forms be stored by the Principal Investigator, in a locked cabinet, on University premises?

YES

7. Are Consent Forms stored separately from data and kept for six years?

YES

SECTION E: STORAGE AND USE OF RESULTS

1. Will the participants be audio-taped, video-taped, or recorded by any other electronic means such as Digital Voice Recorders?

(Explain in the PIS and CF. Consider whether recording is an optional or necessary part of the research design, and reflect this in the CF.)

YES

2. a) Will the recordings be transcribed or translated?

NO

b) Who will be transcribing the recordings?
(If someone other than the researcher is the transcriber, attach a copy of the Confidentiality Agreement and indicate in the PIS and CF.)

RESEARCHER

c) If recordings are made, will participants be offered the opportunity to edit the transcripts of the recordings?

NO

d) Will participants be offered their tapes or digital files of their recording (or a copy thereof)?

NO
Appendix: Human Participants Ethics Application

3. If a questionnaire is used, please explain any coding scheme (if any) that is used to identify the respondent.
   (For example: Questionnaires are numbered 1-999 and a list is maintained to link participants with the questionnaire).

   | NO |

4. a) Explain how and how long the data (including audio-tapes, video-tapes, digital voice recorder, and electronic data) will be stored.
   (Indicate this in the PIS. The period data is to be kept will be commensurate to the scale of its research. For peer reviewed publication that might be further developed, the University expects six years.)

   Data will be stored as electronic memory until the end of the research project.

   | b) Explain how data will be used.
   (Indicate this in the PIS.)

   Data will be used to verify the accuracy of biomechanical models and to develop a method for calibrating the device to the user.

   | c) Explain how data will be destroyed.
   (Indicate this in the PIS.)

   Electronic data will be deleted from memory.

5. Describe any arrangements to make results available to participants.
   (Explain this in the PIS.)

   N/A (researcher is participant)

6. a) Are you going to use the names of the research participants in any publication or report about the research?
   (The PIS must inform the participants, and be part of the consent obtained in the CF.)

   | NO |

   b) If you don’t use their names, is there any possibility that individuals or groups could be identified in the final publication or report?
   (This is a problem either when one is dealing with a small group of participants known to a wider public or when there is to be a report back to participants likely to know each other.)

   | NO |

SECTION F: TREATY OF WAITANGI

1. Does the proposed research have impact on Māori persons as Māori?

   | NO (Go to Section G.) |
2. Explain how the intended research process is consistent with the provisions of the Treaty of Waitangi.
(Refer to the Applicants’ Manual 2010 for further information.)

N/A

3. Identify the group(s) with whom consultation has taken place, describe the consultation process, and attach evidence of the support of the group(s).

N/A

4. Describe any on-going involvement the group(s) consulted has in the project.

N/A

5. Describe how information will be disseminated to participants and the group consulted at the end of the project.

N/A

SECTION G: OTHER CULTURAL ISSUES

1. Are there any aspects of the research that might raise any specific cultural issues?

NO (Go to Section H)

2. What ethnic or cultural group(s) does the research involve?

N/A

3. Identify the group(s) with whom consultation has taken place, describe the consultation process, and attach evidence of the support of the group(s).

N/A

4. Describe any on-going involvement the group(s) consulted has in the project.

N/A

5. Describe how information will be disseminated to participants and the group(s) consulted at the end of the project.

N/A
SECTION H: CLINICAL TRIALS

1. Is this project a Clinical Trial?
   - NO (Go to Section I)

2. Is this project initiated by a Pharmaceutical Company?
   - NO

3. Are there other NZ or International Centres involved?
   - NO

4. Is there a clear statement about indemnity?
   - NO

5. Is Standing Committee on Therapeutic Trials (SCOTT) approval required?
   - NO

6. Is National Radiation Laboratory approval required?
   - NO

7. Is Gene Therapy Advisory Committee on Assisted Human Reproduction (NACHDSE) approval required?
   - NO

SECTION I: RISKS AND BENEFITS

1. What are the possible benefits to research participants of taking part in the research?
   - N/A (researcher is participant)

2. What are the possible risks to research participants of taking part in the research?
   - Injuries caused by malfunction of rehabilitation device
   (Make sure that you have clearly identified/explained these risks in the PIS and CF(s).)
3. a) Are the participants likely to experience discomfort (physical, psychological, social) or incapacity as a result of the procedures?

NO

b) What other risks are there?

N/A

c) What qualified personnel will be available to deal with adverse consequences or physical or psychological risks?

(Explain in the PIS.)

N/A

SECTION J: FUNDING

1. Have you applied for, or received funding for this project?

YES (Acknowledge it on the PIS and answer either 2 or 3 below.)

2. From which funding bodies? (Quote the contract reference number.)

University of Auckland Doctoral Scholarship

3. Is this a UniServices project?

NO

4. Explain investigator’s financial interest, if any, in the outcome of the project.

N/A

5. Do you see any conflict of interest between the interests of the researcher, the participants or the funding body?

NO (researcher is participant)

SECTION K: HUMAN REMAINS, TISSUE AND BODY FLUIDS

1. Are human remains, tissue, or body fluids being used in this research?

NO (Go to Section L.)
2. **How will the material be taken?**  
(For example: at operation, urine samples, archaeological digs, autopsy.)

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3. **Is the material being taken at autopsy?**

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4. **Is material derived or recovered from archaeological excavation?**

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5. **Will specimens be retained for possible future use?**

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   a) **Where will the material be stored?**

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   b) **How long will it be stored for?**

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6. a) **Will material remain after the research process?**

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   b) **How will material be disposed of?**  
(Explain how the wishes with regard to the disposal of human remains of the whanau (extended family) of similar interested persons will be respected.)

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   c) **Will material be disposed of in consultation with relevant cultural groups?**

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7. **Is blood being collected?**

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Appendix: Human Participants Ethics Application

a) What is the volume at each collection?

N/A

b) How frequent are the collections?

N/A

c) Who is collecting it?

N/A

d) Explain how long it will be kept and how it will be stored.

N/A

e) Explain how it will be disposed of.

N/A

SECTION L: OTHER INFORMATION

1. Have you made any other related applications?

NO

2. If there is relevant information from past applications or interaction with UAHPEC, please indicate and attach.

N/A

3. Are there any other matters you would like to raise that will help the Committee review your application?

NO

--- END OF APPLICATION FORM ---
Risk Management Plan

Description of Project
The project involves the development of a wearable robotic device for the rehabilitation of the human arm. Three experiments are required during the development stage in which there is a risk of injury to the user. All movements in the experiments will be within the range of motion of the human joints and at velocities lower than that achievable by the human joints. An iterative technique will be used in the experiments in which a cycle of experimentation and fine-tuning of the model and/or algorithm will occur until sufficiently accurate results are achieved. The purpose and process of these experiments are briefly described below.

Experiment 1
Purpose: To obtain biomechanical data from the user’s arm for model development.
Process: User voluntarily moves arm while wearing the inactive device. Sensors measure dynamic information during the experiment.

Experiment 2
Purpose: To test and optimise control of the device.
Process: The device moves the user’s arm through a pre-planned path trajectory.

Experiment 3
Purpose: To test and optimise calibration of the device with the user.
Process: A combination of the user moving the device and the device moving the user’s arm.

Potential Risks
Experiment 1 has minimal risk of injury since the device does not generate forces on the arm. Experiment 2 and 3 can cause injury if the device malfunctions or an error occurs. Injury can occur from over extension of the joints or abrupt movements. The device is driven by air muscles which operate on compressed air. As a result, there is minimal risk of electric shocks as only low voltage electronics are used.

Safety Measures
Safety measures will be enforced in the hardware, electronics and software to minimise the risk of injury.

Hardware
- Mechanical stoppers will be attached to the device to block the joint from extending beyond safe limits.
- The air muscles used have a ‘soft’ nature. This gives the device high compliance which minimises sudden jerk movements.

Electronics
- Emergency stop button will allow the user to manually freeze the device and release the air pressure inside the air muscles.

Software
- Sensors will constantly monitor the operation of the device and limit the force, position, velocity and acceleration within safe threshold levels. Operation outside the safety limits will trigger the device to freeze and release air pressure.
- A computer model of the device and human arm will be used to simulate the experiments to ensure the device operates as intended before actual testing is done.
CONSENT FORM
(from Manager)
THIS FORM WILL BE HELD FOR A PERIOD OF 6 YEARS

Project title: Development of a Wearable Exoskeleton Robot for Upper Limb Rehabilitation and Power Assist
Name(s) of Researcher(s): Ho Shing Lo

I, as the researcher, understand the nature of the research. I voluntarily choose to participate as the participant in the research project.

- I agree to take part in this research.
- I understand that I will be required to physically interact with the rehabilitation device and the risks involved in these interactions.
- I understand that I am free to withdraw participation at any time.
- I agree to be videotaped.
- I understand that data will be kept for 6 years, after which they will be destroyed.
- I understand that my personal information will be kept confidential

Name ___________________________
Signature ___________________________      Date _______________

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ON .......... for (3) years, Reference Number 2011/146
References


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C. L. Hwang and A. S. M. Masud, Multiple objective decision making, methods and applications: a state-of-the-art survey: Springer-Verlag, 1979.


References


References


