

University of London
Imperial College of Science, Technology and Medicine
Department of Computing

**Developing a Lower-Limb Soft Exosuit for
Human Rehabilitation and Space Application**

Shamas Ul Ebad Khan

CID: 01155174

Supervisor: Professor Etienne Burdet

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Abstract

This thesis presents a novel design for a lower limb soft exosuit that employs pennate-style actuators and shape memory polymers to enhance resistive exercise regimens with particular consideration for astronaut-specific needs. An essential issue during extended periods of space travel and habitation is the degradation of the musculoskeletal, cardiological and neurological systems. In designing the exosuit, the goal is to address the musculoskeletal system's degradation.

The present study identifies and fills a significant gap in space research based on an extensive literature review. By exploring recent advancements and established understandings in soft robotics, space medicine, and materials science, astronauts will gain a comprehensive understanding of the musculoskeletal challenges they are likely to encounter in microgravity environments.

In light of this solid foundation of understanding, a novel exosuit design is presented. Using a pennate-style actuator, the exosuit design may provide sufficient resistance and actuation efficiency, mimicking the architecture and operation of human muscles. Furthermore, the exosuit design utilises shape memory polymers, which provide morphological adaptability and energy efficiency. The suit is made from materials that conform to the specific physical characteristics of the user and respond to the demands of exercise.

At this stage, the thesis outlines a conceptual design of the exosuit without implementing prototypes or experimenting with it. Consequently, it lays the foundation for subsequent research to bring to life this concept by elucidating potential methodologies for these future steps.

For prolonged and deeper space missions, astronauts are challenged to maintain their health, which is a pressing issue. Its comprehensive exploration and innovative design lays the foundation for future research in space biomechanics, soft robotics, and astronaut physiology.

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Abbreviations

- ADL - Activities of Daily Living
- AGR – Architectural Gear Ratio
- ANP – Atrial Natriuretic Peptide
- ANS – Autonomic Nervous System
- ARED – Advanced Resistance Exercise Device
- BCI – Brain Computer Interface
- CHF – Chronic Heart Failure
- CNS – Central Nervous System
- CO – Cardiac Output
- CPU – Computer Processing Unit
- CVP – Central Venous Pressure
- DGC – Dystrophinglycoprotein Complex
- DOF – Degrees of Freedom
- DTW – Distal Thigh Webbing
- EDV – End Diastolic Volume
- EEG – Electroencephalogram
- EMG - Electromyogram
- EMG – Electromyography
- EVA – Extra Vehicular Activities
- FES – Functional Electrical Stimulation

- FRED – Functional Resistive Exercise Devices
- G – Gravity
- GI – Gastro Intestine
- HNP - Herniated Nucleus Pulposes
- HR – Heart Rate
- HRV – Heart Rate Variability
- IADL – Instrumental Activities of Daily Living
- IRED – Interim Resistance Exercise Device
- ISS – International Space System
- IVD – Inter-Vertebral Discs
- LEO – Low Earth Orbit
- M – Intrinsic Vectors
- MAP – Mean Arterial Pressure
- MCFP – Mean Circulatory Filling Pressure
- MRI – Magnetic Resonance Imaging
- NASA - National Aeronautics and Space Administration
- NHS – National Healthcare Systems
- nNOS – neuronal Nitric Oxide Synthase
- NO – Nitrogen Oxide
- OI – Orthostatic Intolerance
- OKAN – Optokinetic After Nystagmus

- OKN – Optokinetic Nystagmus Reflex
- PA – Passive Actuation
- PAM - McKibben Pneumatic Artificial Muscles
- PCSA – Physiological Cross Section Area
- PRT – Progressive Resistance Training
- PTFE – Polytetrafluoroethylene
- PTW – Proximal Thigh Webbing
- RF – Rectus Femoris
- RM – Revolutions per Minute
- RNA – Ribonucleic Acid
- SABP – Space Adaptive Back Pain
- SCI – Spinal Cord Injuries
- SEA – Series Elastic Actuators
- sEMG – Surface Electromyography
- SMA – Shape Memory Alloy
- SMP – Shape Memory Polymers
- SMS – Space Motion Sickness
- SNS – Sympathetic Nervous System
- SV – Stroke Volume
- TCA – Twisted Coil Actuators
- TPR - Total Peripheral Resistance

- V – Visual
- VI – Vastus Intermedius
- VL – Vastus Lateralis
- VM – Vastus Medialis
- VOR – Vestibular-ocular Reflex
- VR - Venous Return

Chapter 1

Introduction

As life expectancy increases, the ageing population grows, and the population of people aged above 60 is likely to surpass the billion point within the next decade (Population Division and Affairs 2017). The incidence of medical ailments and trauma in the elderly is also expected to rise significantly. One of the challenges the elderly face is the loss of muscle strength and bone loss due to ageing, trauma or an ailment that restricts them from carrying out *activities of daily living* (ADL). This results in a poor quality of life and leaves the elderly dependent on some form of physical aid, both at home and during rehabilitation (Goldspink 2012). Consequently, this mounts pressure on the *National Healthcare Systems* (NHS), the staff working in rehabilitation, as well as causing a marked financial burden. Wearable robotics reflect a promising outlook in developing novel solutions for medical rehabilitation, health monitoring, and restoring mobility to assist in ADL. It has attracted a range of disciplines from industries to the military for physical human augmentation and preventive measures. In the past, researchers have focused on developing exoskeletons, a rigid mechanical framework, on assisting and rehabilitating people with paraplegia or those with mobility and gait issues resulting from stroke, *spinal cord injuries* (SCI) or other trauma (Chen et al. 2016). These exoskeletons provide assistive forces and torques at the joints to aid movement at the desired and intended pathways, either in gait, movement or in heavy load lifting tasks. Exoskeletons have also attracted space agencies as space crew members in spaceflight undergo muscle atrophy and bone

resorption due to microgravity (Lang et al. 2017). Consequently, astronauts participate in intensive exercise protocols during spaceflight to prevent microgravity-induced effects. Therefore, instead of providing assistive forces, exoskeletons are being designed as a countermeasure to provide resistive forces in the absence of gravity to enable space crew members to carry out resistive exercises.

Many medical disciplines adopt progressive resistance exercise protocols as a rehabilitation tool. In gerontology, the elderly population undergo resistive exercises to compensate for the age-related loss of muscle mass known as sarcopenia (Kraemer, Ratamess, and French 2002) and in particular to those who suffer stroke (Flansbjerg, Lexell, and Brogårdh 2012) and Parkinson’s disease (Lima, Scianni, and Rodrigues-de-Paula 2013). People suffering from muscle dysfunction due to *chronic heart failure* (CHF) or Cardiomyopathy have also shown an improvement in muscle strength and quality of life with resistive exercises (Jewiss, Ostman, and Smart 2016). Resistive exercises show significant improvement in muscle strength for people going through post-traumatic responses, musculoskeletal injuries, and neurological disorders. A balance between resistive exercises and assistive management is equally crucial in offering an improved quality of life and maintaining health. Researchers have also focused on developing exoskeletons for resistance training for various target muscle groups as a preventive tool against muscle atrophy or to increase muscle strength (Wu and Chen 2012; Son et al. 2016).

Current exoskeletons are heavy, bulky and expensive, which may prevent acceptance socio-economically and its translation from clinical use to use at home (Rupal et al. 2017). Rigid exoskeletons also reduce the natural *degrees of freedom* (DOF) and therefore, hindering natural human DOFs and movement, and the addition of weight may increase the metabolic cost that may cause fatigue and discomfort to the user.

Technology advancement, combined with smart textiles, have given rise to the concept of soft exoskeletons, or exosuits. Soft exosuits rely on human-body structure and joints in transmitting moments (Asbeck et al. 2014). They are fabricated with lighter and softer materials to conform and safely align with the human body; therefore, mitigating adverse effects on the normal human kinematics. Their inertia is significantly lesser than traditional exoskeletons and is more

comfortable due to the soft materials (Asbeck et al. 2014; Rus and Tolley 2015), therefore, enhancing its acceptability at a larger scale use and, in space applications. Therefore, the demand for wearable robotics in the medical field, space agencies and in commercial industries will inevitably grow.

Progression is growing in developing effective soft exosuits. Though, the progress is still in infancy. Past research focuses on developing soft exosuits for assistive forces; however, developing soft exosuits for resistance training is under-explored (Rus and Tolley 2015). Therefore, we intend to design a soft exosuit for lower limb extremities for resistance training in addition to assisting with natural mobility. Lower limbs are given preference as most falls in the elderly occurs due to the muscle weakness in those essential muscle groups that account for strokes or other associated disabilities. Besides, lower limb muscles undergo the most considerable muscle atrophy in space crew members during spaceflight. The design for the soft exosuit must mimic the action of skeletal muscles and tendon to transmit required forces at the human joints for safe and effective actuation.

Few of the current challenges in designing soft exosuits involves actuator preference and robust control strategies. Most exosuits designed to date, utilises cable-based actuation using conventional electric, hydraulic or pneumatic actuators (Rus and Tolley 2015). Although electric actuators produce adequate torques for human joint actions, they have a low power-to-weight ratio. Pneumatic and hydraulic actuators require bulky power sources and also, conventional actuators are relatively noisy (Mavroidis, Pfeiffer, and Mosley 1999). The utilisation of soft actuators such as shape memory polymers in exosuits has not yet been tested, largely due to its low-frequency response, low force production, power requirements and excessive heat production (Rus and Tolley 2015; Boyraz, Runge, and Raatz 2018). Therefore, we intend to explore new methods of actuation with soft polymers to transmit adequate forces for the required task in addition to overcoming its disadvantages.

1.1 Motivation and Objectives

This research aims to design a novel soft robotic exo-suit that provides both resistive and assistive forces to the lower limbs. The former should enable the user to perform resistive exercises to prevent muscle atrophy and bone resorption. The latter should aid the user with gait disabilities on Earth to assist in maintaining posture as well as to provide aid in daily living tasks. As for the space crew members, it should aim to assist *extra-vehicular activities* (EVA) in space. The soft exosuit should exert adequate forces on the muscles of the lower limbs and lumbar region. This involves exploring novel techniques for actuation that could be integrated with the soft exosuit and control strategies to enable real-time feedback and increase in performance.

The soft exosuit would aim to support the use-case scenarios below that share common problems and therefore, require a similar solution.

1.1.1 Use Cases and Hypothesis

1. People on Earth undergo muscle atrophy due to - sarcopenia, neuro-muscular disorders, injury or trauma causing significant concern. They require progressive resistance exercises regularly for many months to increase and maintain their muscle strength.

Hypothesis - Compared to traditional rehabilitation methods alone, using a soft exosuit in conjunction with traditional rehabilitation programs can result in faster recovery times for individuals suffering from muscle atrophy due to sarcopenia, neuromuscular disorders, injury, or trauma.

2. People on Earth reduce their ability to perform normal gait or movement due to conditions associated with ageing, trauma, injuries or genetics. These people require assistive devices to help with their ADLs and tasks to improve their quality of living. They require assistive technology to increase their mobility.

Hypothesis - The soft exosuit as an assistive technology can significantly improve mobility of individuals and reduce metabolic cost whose gait or movement has been compromised by ageing,

trauma, injuries, or genetic conditions. This leads to an improved quality of life compared to those using traditional assistive devices alone.

3. An astronaut in space undergoes muscle atrophy and bone resorption in the lower limbs due to microgravity. Therefore, the astronaut requires some resistive mechanism to reduce muscle atrophy and enable strength in addition to muscle growth and bone growth.

Hypothesis - A soft exosuit will provide similar or superior results to the current countermeasure devices in preventing muscle atrophy and bone resorption in astronauts in space.

4. An astronaut could experience fatigue during movement and tasks in EVA in space. This may affect their task performance. Therefore, they require some assistive mechanism to assist them in their tasks during that period.

Hypothesis - Soft exosuits may provide the necessary assistance during EVA tasks in space for astronauts experiencing fatigue, potentially improving their task performance and endurance as compared to astronauts doing EVA tasks without such assistive devices.

Due to the limited amount of time, this research will initially focus on use cases one and three. Following the exploration of these primary use cases, I will extend our research to cover cases two and four, ensuring that all scenarios are covered.

1.1.2 Objectives

1. Design a low-weight, safe and a bioinspired soft-exosuit for users, which provides the resistance needed for lower-limb muscle strengthening.
2. Provided that the first objective is successfully achieved, the next objective is to modify the design in such a way that could also aid users in gait and movement. The exosuit should be able to switch between resistance and assistance mode without any issues.
3. Explore new actuation techniques involving shape memory materials for improved performance that can be integrated seamlessly in the exosuit. In the case of resistance, the actuation should generate and transmit adequate forces to enable strengthening and maintaining the tar-

get muscle strength. In the case of assistance, the actuation techniques should generate safe and adequate forces to enable desired joint movements of the lower limbs without hyper-extension or injury. Switching between the assistance and resistance phase should be reliable.

4. Explore control strategies to provide real-time feedback and actuation. The control strategy should act as an indicator to provide optimum resistance or assistance and should ensure the safety of the device.

1.2 Contributions

This thesis reviews adverse cardiovascular, neurological, and musculoskeletal effects during space missions. This review provides a comprehensive and up-to-date understanding of the potential risks associated with prolonged space travel. This review also focuses on these specific physiological systems as the focus for this review. By synthesising available research, we seek to identify knowledge gaps and suggest potential areas for future investigation, thereby contributing to the field of space medicine and human space exploration.

This thesis has proposed a novel solution by developing a soft exosuit to partially or completely address the adverse physiological effects astronauts experience during prolonged space missions. The purpose of this contribution is to develop and utilise exosuits for the provision of resistive exercise under microgravity conditions. In particular, this thesis aims to provide a novel approach to mitigate astronaut musculoskeletal deterioration during space travel by reviewing the existing literature on exosuit technology and its potential applications in space medicine.

An essential contribution of this thesis is the design of a novel pennate-style actuator that can be integrated into a soft exosuit for lower limb applications. With the proposed actuator, soft exosuits can be enhanced in terms of performance and functionality. It is possible to generate multiple-directional forces with this design, which can result in improved force transmission, joint torque production, and energy efficiency by maximising mechanical advantage. In addition to providing greater comfort and freedom of movement to the wearer, the actuator's flexible nature allows it to be seamlessly integrated into the soft exosuit structure. This contribution

aims to address the challenges associated with soft wearable robotics and present a solution that can significantly enhance the effectiveness of lower limb exoskeletons.

The thesis contributes to the field of soft actuators by advancing the application of shape memory polymers as soft actuator materials and by developing a concept for integrating novel technologies in an efficient and scalable manner. The use of SMPs as actuator materials have been explored previously. However, this contribution builds upon that knowledge and presents enhancements that enhance their effectiveness. It is intended to bridge the gap between research and practical applications by incorporating innovative technology to address the challenges in soft robotics.

An essential contribution of this thesis is identifying gaps in the existing research on soft exoskeletons by proposing a comprehensive kinematic analysis study. Despite the increasing attention given to soft exoskeletons over the past few years, it remains necessary to understand the kinematic behaviour and performance of these systems across a wide range of tasks and populations of users. The purpose of this study is to provide valuable insights into the current gaps in knowledge regarding soft exoskeletons by conducting a systematic kinematic analysis.

1.3 Statement of Originality

I herewith certify that all material in this thesis which is not my own work has been properly acknowledged.

1.4 Publications

Khan, S. U.E., Rosa, B. G., Kassanos, P., Miller, C. F., Deligianni, F. and Yang, G.-Z. (2021) Physiological adaptations in space and wearable technology for biosignal monitoring. In: Space Robotics and Autonomous Systems. IET

Khan, S. U.E., Varghese, R., Kassanos, P., D., Farina, and Burdet, E. (2023) Space Physiology and Technology: Musculoskeletal Adaptations, Countermeasures, and the Opportunity for Wearable Systems. Unpublished (Submitted)

Chapter 2

Background Theory

2.1 From the adolescent to the elderly – muscle weakness and disabilities

Frailty and muscle weakness in older adults or the elderly are decisive risk factors in causing falls, leading to a cascade of physiological complications (Moreland et al. 2004). The risk of having a fall increases with age, and at least 30% of the population above 65 has a fall once in their lifespan (Peeters, Schoor, and Lips 2009). Such occurrences make the person more dependent upon physical assistance or revert the elderly to residential nursing homes requiring long-term rehabilitation (Peeters, Schoor, and Lips 2009). Muscle weakness in the lower extremities poses a greater risk of contributing to falls than weakness in the upper extremities, subsequently forming physical disability and functional limitations (Orr 2010; Hairi et al. 2010). Muscle power reduction in the lower limbs due to physical inactivity has been associated with reduced mobility and balance, also leading to falls or diseases such as sarcopenia in the elderly.

A substantial proportion of the elderly and older adult population has a prevalence of functional limitations in mobility, lifting, and ADL due to a higher prevalence of frailty (figure 2.1). Gale et al. (Gale, Cooper, and Aihie Sayer 2015) found that mobility is the most significant limiting factor for frail or non-frail elderly populations by 93 % and 58 %, respectively. Limitations

on ADLs and *instrumental ADLs* (iADL) were not remarkable by the non-frail; however, the frail had a prevalence of limitation of about 57 % and 65 %, respectively. Reduced mobility and inability to perform ADLs reduce the quality of life. A common factor with frail adults is reduced speed due to loss of muscle strength and balance, contributing to a higher risk of falls (Giné-Garriga et al. 2014). Leg strength, in particular the extensors, the level of physical activity, gait speed, and cognitive impairments are essential parameters in predicting adults acquiring ADL disability, such that adults with lower leg strength are at higher risk (Ouden et al. 2013). Studies indicate that countermeasures, such as exercise, significantly reduce the prevalence of these limiting factors (Giné-Garriga et al. 2014; Chou, Hwang, and Wu 2012). There are various exercise training protocols in research, like *progressive resistance training* (PRT), endurance, agility, flexibility or balance training to improve ADLs, quality of life and mobility.

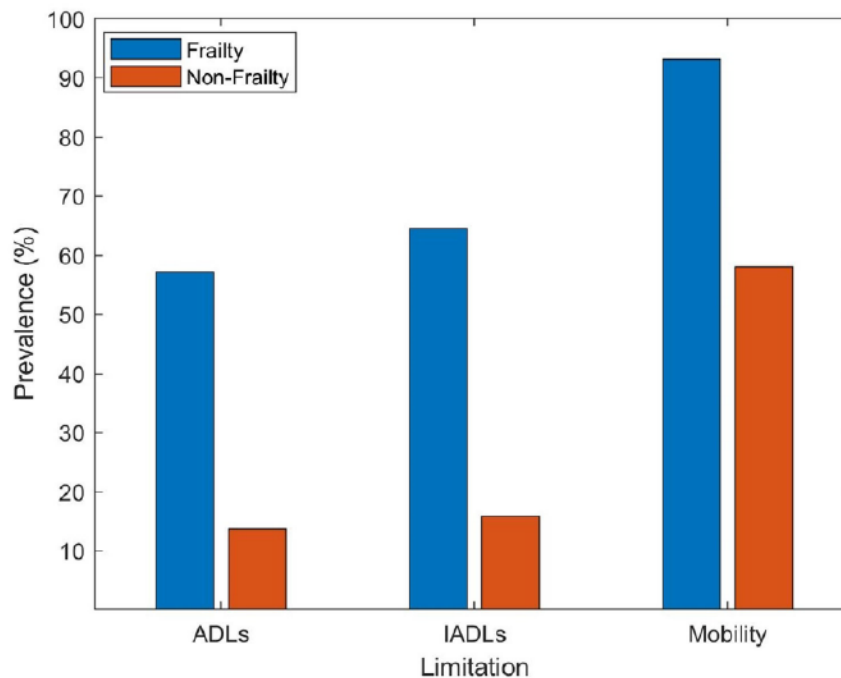


Figure 2.1: Comparison of prevalence between Frail and Non-Frail in different limitations for above aged 60. Number of Participants: **Frailty = 644** and **Non-frail = 4806**. Prevalance figures taken from Gale et al. (2015) * ADLs - Activities of Daily Living ** IADLS - Instrumental Activities of Daily Living

Research indicates that PRT alone in the elderly increases muscle strength significantly, improves postural stability, and reduces the risks of falls and injuries (Serra-Rexach et al. n.d.;

Liu-Ambrose et al. 2004; Liu and Nancy K Latham 2009; Bunout et al. 2005; Wang and Pessin 2013). However, low-intensity training studies found inconsistent evidence for improved balance compared with high-intensity training studies (Liu-Ambrose et al. 2004; Nancy K. Latham et al. 2003). The study participants have tolerated these training protocols, whether low or high intensity, with some functional benefits. Combining this training programme with balance or agility training, known as multicomponent training, has significantly reduced the incidence of falls and improved functional performance (Karlsson et al. 2013). However, these training methods are staff intensive, in a controlled environment, and dependent upon the compliance of participants attending every session (Liu-Ambrose et al. 2004). Therefore, with the increased demand for care required for preventive or rehabilitative purposes with the rise of the ageing population of older adults above 60, the quality of care may not be at its highest level, inevitably affecting the recovery rate and the quality of life.

Inactivity or disuse of muscles could lead to significant loss of muscle strength, muscle atrophy and fatigue (Scherbakov et al. 2013; Narici and Maffulli 2010). It is beyond the scope of this thesis to review the reasons behind muscle atrophy and fatigue; however, suggestively, it is due to shifting in fibre phenotypes in muscles, reduction of motor innervation, and sensorimotor deficits (Narici and Maffulli 2010). These can occur in any phase of life, from adolescence to the elderly and could reduce the quality of life. Inactivity or immobilisation also increases insulin resistance, impairs anabolic stimulation, and reduces lean mass and muscle strength (Scherbakov et al. 2013). Therefore, rehabilitation is always necessary to recover muscle strength, restore motor control, and regain independence. Almost all rehabilitation programmes involve resistance training protocols.

High-intensity resistance training in stroke patients with hemiplegia has increased balance, gait, and muscle strength by 8.9 %, 10.6 %, and 9.4 %, respectively, in a study by Fernandez-Gonzalo et al. (2016). The quadriceps had the most significant hypertrophy, with noticeable muscle strength and power increase. The authors indicate that eccentric overload resistance training, not concentric overload resistance training, promoted neural adaptations and cognitive performance. Resistive and aerobic training improved gait speed, muscle strength and balance in another study (Lund et al. 2018). However, the authors

concluded that improving balance is not a prerequisite for improving the functional capacity of stroke patients. Inconclusive evidence exists in the studies on whether resistive training in stroke patients could promote this activity. However, muscle strength was significantly improved (Dorsch, Ada, and Alloggia 2018). Comparing Alzheimer’s disease patients with social gathering group control, Garuffi et al. (Garuffi et al. 2013) found that resistance training significantly improved functional capacity and agility in moving around, climbing stairs, rising from the floor, or wearing socks. Improved muscle strength of the lower limbs, especially the quadriceps, is attributed to increased performance. Long-term PRT, in addition to aerobic training, has also been shown to improve muscle strength, muscle power, and functional capacity in people with Parkinson’s disease, which has improved ADL and quality of living (Dibble et al. 2009; Briennesse and Emerson 2013). High-intensity eccentric training has been found to be the most effective exercise (Dibble et al. 2009).

People with diseases causing complete paralysis, severe muscle strength and volume loss, and inability to participate in resistance training requires some assistive technology. More than 20 million people have an ambulatory disability in the USA alone (Erickson, Lee, and Von Schrader 2019), and more than 1 billion people may require at least some assistive technology by 2030 (Population Division and Affairs 2017). This demographic encompasses a broad range of people, including but not limited to those with debilitating conditions such as severe multiple sclerosis, total paralysis due to stroke, paraplegia, Parkinson’s disease, and traumatic injuries resulting in amputations and loss of motor control. These technological interventions are aimed at restoring locomotion, assisting with activities of daily living, and improving functional capacity, which ultimately fosters independence by compensating for the impaired muscles (Lansley, McCreadie, and Tinker 2004). Furthermore, these assistive technologies play a critical role in facilitating neurological and orthopaedic rehabilitation programs, providing a comprehensive solution to diverse health challenges. Assistive technology includes but is not limited to prostheses, orthosis, wheelchairs, exoskeletons and *brain-computer interface* (BCI). Numerous initiatives have emerged over the past decades to promote the development of assistive technology for individuals with profound physical disabilities. Among these projects, the Cybathlon stands out as an exceptional and influential event that has spurred ground-breaking research

and development in assistive technology (Riener 2016). Such global competitions attract researchers from all fields to collaborate and compete to produce assistive technology to facilitate ADL. The Cybathlon competition, held every four years features six distinct disciplines, from exoskeletons to brain-computer interfaces, with challenges that test assistive device capabilities.

Recent studies have uncovered critical concerns regarding the use of assistive technology among older adults and the elderly. Yusif et al. (2016) found that privacy, efficacy for daily use, training, and fear of dependence were pressing concerns among the aged population. Barker, Reid, and Cott (2006) found a shortage of medical work-staff and that wheelchair or assistive technology users still created some form of dependence on others, such as nurses or family members. Negative perceptions towards assistive technologies also emerge as a critical factor in their usefulness (Carver et al. 2015). For example, Chaves et al. (2004) revealed that some users negatively perceived these technologies regarding social acceptability, fear, and negative attention seeking. It was also found that the psychological dependency may undermine its positive effects (Silver et al. 2012). Nonetheless, enhancing the quality of living for some users provided a new beginning, and its advantages cannot be overlooked.

It is apparent that both resistance training and assistive technology share a common challenge of relying on staff assistance and being resource-intensive to varying degrees. The cost of these devices is also a concern to prospective users that hinders them from adopting these technologies. Therefore, a need exists for cost-effective technologies for which wearable robotics hold tremendous potential. Notably, such innovations could also address the rehabilitation needs of astronauts in space, who experience health complications akin to those of the elderly. The health problems that typically afflict the elderly over the years may arise in astronauts within weeks of being in space. By devising solutions to enhance the health and well-being of astronauts, researchers could develop cutting-edge solutions for a much larger global population.

2.2 Astronauts in space - physiological adaptations

As astronauts venture into space, hydrostatic pressure on the body tissues diminishes, resulting in a cephalic fluid shift. The face becomes puffy, along with nasal congestion and a feeling

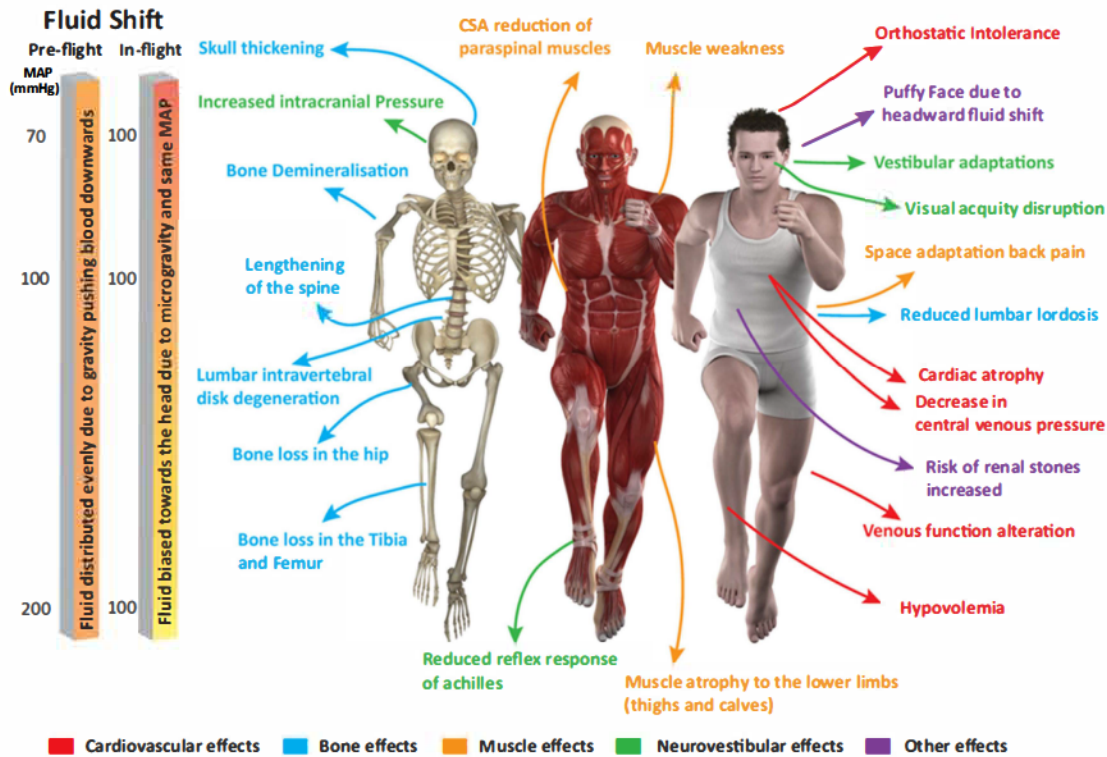


Figure 2.2: Physiological adaptations in space. Figure of human anatomy have been sourced and modified from Shutterstock.com (Licensed stock illustration - 182406275).

of fullness of the upper body (figure 2.2). These fluid shift triggers a complex cascade of physiological responses leading to various physiological adaptations (Khan et al. 2021), with the neuro-vestibular and cardiovascular systems being one of the first affected.

2.2.1 Cardiovascular adverse effects during spaceflight

Fluid redistribution activates various human receptors, such as baroreceptors, mechanoreceptors, and proprioceptors. Baroreceptors are located in the carotid and aortic arches. They transmit information about blood pressure to medullary pathways that regulate the sympathetic or parasympathetic pathways of the *autonomic nervous system* (ANS). In space, conflicting results have been reported, such as some have reported a decrease in the *heart rate* (HR) and *heart rate variability* (HRV) (Fritsch-Yelle et al. 1996; Migeotte, Prisk, and Paiva 2003), whilst others have observed unchanged effects (Verheyden et al. 2009; Baevsky et al. 2007), or an increased HR and HRV due to increased SNS and derangement of vagal baroreflex function (Eckberg et al. 2010).

A reason for the conflicting results may be the choice of the reference position on Earth (Khan et al. 2021). Measurements taken in a supine position may differ significantly from those taken in seated positions. For instance, blood pressures are typically lower in the supine position compared to the seated position (Privšek et al. 2018), while *cardiac output* (CO) is generally higher in the seated position compared to the supine position (Bevegård, Holmgren, and Jonsson 1960). The choice of reference can drastically impact the interpretation of the results. This phenomenon may also explain the conflicting findings reported in the studies conducted by Norsk et al. (2015) and Hamilton et al. (2011). The former observed an increased CO by at least 41 % in space, whereas latter found no changes in CO. The difference in these findings could be attributed to the fact that Norsk et al. (2015) used a seated position as their reference point on Earth, whereas latter measured against a supine position. However, one of the reasons for increased CO may be due to increased *stroke volume* (SV) due to the cephalic fluid shift in the study of Norsk et al. (2015) as HR remained unchanged. CO is directly proportional to SV and HR.

On Earth, supine positioning of the human increases the *end-diastolic volume* (EDV), which in turn increases the SV by the Frank-Starling mechanism (Sundblad and Wranne 2002). Therefore, this may be why the CO increases without changes to the HR. However, one of the critical reasons for increased SV may rise due to the alterations of the *central venous pressure* (CVP). CVP is the pressure in the vena cava before the right atrium (Smetkin and Kuzkov 2021). While fluctuations in CVP on Earth are rare, it generally decreases in weightlessness (Vernice et al. 2020). CVP measurements during the initial phase of a space mission are around 6.2 mmHg (Foldager et al. 1996), similar to the measurements of a human in a supine position on Earth. The mechanisms behind this are still disputed. For instance, White and Blomqvist (1998) postulated that the decrease in CVP is explained by a decrease in intrathoracic pressure that increases transmural pressure and, thus, a reduction in CVP. In contrast, West and Prisk (1999) were sceptical about measuring intrathoracic pressure in the study as they argued that studies have found that the reduction of intrathoracic pressures was too small that could be attributed to a considerable reduction of CVP. However, in support of White and Blomqvist (1998), another study found that a decrease in intrathoracic pressure was larger than CVP

due to chest wall expansion that increased cardiac transmural pressures (Videbaek and Norsk 1997). In general, a decrease in intrathoracic pressures reduces CVP. As a result, the pressure gradient between *mean circulatory filling pressure* (MCFP) and CVP raises that increases the venous return (Gelman, D. S. Warner, and M. A. Warner 2008) and, in theory, should increase CO and SV.

Another cause for reduced CVP in space is sometimes attributed to low blood plasma volume, known as hypovolemia (Vernice et al. 2020; Gelman, Warner, and Warner 2008). Hypovolemia causes a shift of stressed blood to unstressed blood in the veins (Gelman, Warner, and Warner 2008). Instantaneous hypovolemia due to weightlessness may be treated as a 'shock', resulting in compensatory mechanisms and increasing the SNS activity and cardiac contractility to increase the venous return (Taghavi, Nassar, and Askari 2022). However, the fluid shift may induce reflexes (Gauer-Henry's reflex) that may act as an antagonist to the SNS activity by increasing vagal activity and increasing the secretion of *atrial natri-uretic peptide* (ANP) (Pendergast et al. 2015). Early Skylab spaceflight found increased ANP levels in astronauts. This increase in turn facilitates natriuresis, resulting in extracellular fluid reduction through upregulating sodium renal excretion, reducing blood volume, and increasing vasodilation and permeability (Khan et al. 2021). As a result, stimulation of such receptors resulted in a 10 % to 15 % reduction in plasma volume (Vernice et al. 2020).

Astronauts were also found to have lower limb vascular resistance during spaceflight (Fortrat et al. 2017) despite increased SNS activity. This is because SNS-mediated vasoconstriction does not affect veins and venules in skeletal muscles. Furthermore, the jugular and femoral veins remain distended (Arbeille et al. 2001) during spaceflight, activating their respective receptors. Both of these effects may reduce systemic vascular resistance. Norsk et al. (2015) found a 39 % decrease in total peripheral resistance in astronauts. As a compensatory mechanism, this effect may reduce CVP but increase SNS activity to promote vasoconstriction in attempting to increase VR, CO, and SV to maintain *mean arterial pressure* (MAP) and homeostasis. MAP is directly proportional to CO and TPR. Therefore, taking this into account, the cardiovascular system in space undergoes complex adaptations mediated by hormonal changes, ANS, reflex mechanisms, and metabolism changes to adapt to the extreme environment of space.

On Earth, the cardiovascular system adapts to different body positions to meet its metabolic demand and compensate for gravity. The absence of gravity in the ISS decreases the heart workload as it no longer has to adapt to the gravitational force on Earth to maintain locomotion and postural stability (Gregory 2009). This adaptation becomes problematic when space crew members return to Earth as the heart has to compensate against gravity again. Consequently, humans returning from space experience pre-syncope due to their inability to maintain blood pressure in an upright position. This adverse effect is known as *orthostatic intolerance* (OI). Almost 60 to 80 % of astronauts in a retrospective study were found to experience OI after long-duration space missions (Meck et al. 2001). Such high rates are concerning and potentially fatal if astronauts perform emergency evacuations or mobilisation. Some astronauts suffer OI for many days or weeks after post-flight depending on the spaceflight duration (Yates, Bolton, and Macefield 2014). Early theories attributed this effect to the suppression of SNS functionality or hypovolemia (Giris et al. 1997). However, astronauts were found to have regular SNS activity in space (Wieling, Halliwill, and Karemaker 2002), and not all astronauts with hypovolemia experienced OI post-flight. Furthermore, astronauts taking fludrocortisone, a medicine that increases plasma volume, also experienced pre-syncope post-flight, which negated the theory of hypovolemia solely causing OI (Khan et al. 2021).

Astronauts who failed the 10-min standing test post-flight were found to have lower norepinephrine levels, TPR, and blood pressure. Additionally, post-flight syncope and OI were more prevalent in astronauts with higher pre-flight vagal activity (Khan et al. 2021). On Earth, transitioning from sitting to standing results in a sudden drop in blood pressure as gravity pushes the blood towards the legs. To counteract this, SNS activity increases to prevent venous pooling and maintain MAP and cerebral perfusion. This compensatory reflex enables postural stability and prevents falls or syncope. This also involves increased engagement of skeletal muscle pumps and vessel constriction to increase venous return. However, these mechanisms can become impaired in individuals with muscle wasting and decreased muscle tone (Wieling, Halliwill, and Karemaker 2002). Studies have also found reduced left ventricular mass and volumes in ground-based studies and astronauts post-flight. In addition, vascular resistance and SV were reduced compared with pre- and post-flight levels that reduced CO.

Such adaptation may also increase the risk of syncope or a fall.

In general, multiple factors contribute to the prevalence of OI in astronauts. It is hypothesised that OI may result from autonomic balance impairment due to an imbalance of vagal and sympathetic activity and muscle pump impairments. In another explanation, Baran et al. (Baran et al. 2021) attributed poor heart contractility due to heart remodelling and cardiac atrophy in space to OI or syncope. Other theories relating to OI include muscle atrophy, increased venous pooling, and compliance or change in catecholamine hormone levels (B. J Yates and I. A Kerman 1998). Recently, researchers have also explored the contribution of neuro-vestibular system deconditioning to OI (Hallgren et al. 2015). This system provides postural movement and spatial orientation information to the brain, influencing the cardiovascular system to maintain blood pressure in changing human body positions (Yates, Bolton, and Macefield 2014). Evidence exists that the neuro-vestibular system selectively regulates SNS output in postural changes, especially changes in head positions. Therefore, adaptation or plasticity of the neuro-vestibular system may increase susceptibility to OI (Kerman and Yates 1998). Further exploration of the neuro-vestibular system and its adaptations in space can enhance our understanding of these complex issues.

2.2.2 Neuro-vestibular adverse effects during spaceflight

The neuro-vestibular system provides balance and posture information to the brain (Lawson, Rupert, and McGrath 2016). The vestibular system entails semicircular canals that sense head rotational movements in addition to utricles and saccules, known as otolith organs, that sense linear motion of both horizontal and vertical accelerations, respectively (Besnard et al. 2018; Kandel, Schwartz, and Jessell 1991). The latter can also sense orientation relative to gravity. The vestibular organs per se cannot ‘accurately’ distinguish head or body motions until the integration of other sensory inputs from the visual and somatosensory systems are received (Kandel, Schwartz, and Jessell 1991). All these sensory inputs are relayed into the brain stem and cerebellum to be further processed in the higher cortical areas.

The brain also governs attention and cognitive processing that facilitates decision-making,

spatial orientation, hand-eye coordination, locomotion, and balance. A stream of sensory inputs from proprioceptive, haptic, visual, and auditory systems into the brain is responsible for self-consciousness that relays to action, memory consolidation, emotions, and reactions. In other words, the summation of sensory inputs creates ‘perception’, and likewise, the summation of motor inputs creates ‘action’ (Kandel, Schwartz, and Jessell 1991). Space adaptations to the brain occur. However, the underlying causes of such adaptations are not fully understood (Ritsher et al. 2007).

During spaceflight, the constant gravitational force acting on the otolith organs is diminished, resulting in reduced sensitivity to linear acceleration and tilt. In the wake of this deconditioning, astronauts may experience balance impairment and spatial disorientation. Particularly, upon their return to Earth, they may be unable to adapt to gravity-dependent tasks, which may also contribute to OI. Otolith deconditioning can take from a few days to a couple of weeks to recover. Most astronauts showed significant improvement in their balance ten days after landing (Moore et al. 2019). To facilitate their recovery, astronauts typically undergo rehabilitation programmes.

Space motion sickness (SMS) is another short-term effect observed during space missions. Almost every astronaut experiences SMS upon arriving into space or returning to Earth, which can last two to three days (Williams et al. 2009). SMS occurs mainly during transitions between the gravitational fields, when attention and cognitive functionality are of utmost importance (Williams et al. 2009; Graybiel, Miller, and Homick 1975). The symptoms associated are, yet not limited to, nausea, headaches, and drowsiness (Clément and Reschke 2008a; Lackner and DiZio 2000). The underlying mechanisms of SMS are inconclusive, although various theories exist. One proposed theory is sensory conflict theory, which suggests SMS occurs due to conflicting information between sensory inputs between the semicircular canals, otoliths, or visual systems and the anticipated signals (Clément and Reschke 2008a).

As the vertical vector is affected in spaceflights, the role of saccules in otoliths have been given importance by several researchers. Thornton and Bonato (Thornton and Bonato 2013) have considered the adaptation of the evolutionary protective mechanism in humans for the cause

of SMS. They hypothesise that the saccules adapt to weightlessness by positioning themselves into a neutral position such that the cilia on the hair cells are parallel to the vertical vector. The utricles and saccules transmit meaningful signals to the brain. However, the neutral position of the saccules cannot transmit meaningful signals to the neurons for further processing, resulting in a conflict. This mechanism activates the ‘Failsafe Protective Mechanism’ that prevents aggravation of the human motion (Thornton and Bonato 2013). The vestibular system reprograms to disengage the otolith signals within 72 hours that subside SMS. However, the continued intrinsic conflicts in other sensory systems, including the GI, may cause instant episodic vomiting.

Another explanation that simplifies the sensory-conflict theory is the subjective-vertical conflict theory, which infers the mismatch between the subjective vertical and sensed vertical vectors. This theory only involves the altered cues related to gravity from the otoliths (Bles et al. 1998; Chen et al. 2016). The subjective-vertical vector is the internal representation of gravity that entails the stored pre-determined verticality. The subjective-vertical vector is the summation of the *gravity* (G), *visual* (V), and *intrinsic* (M) vectors. The visual vector is the perceived verticality from the visual scene, the gravity vector stores information from our body gravi-receptors from our otoliths and non-vestibular proprioceptive, and the intrinsic vector is the vertical alignment with our body z-axis (Chen et al. 2016). In weightlessness, the mismatch occurs due to the reduced gravity vector that results in a conflict vector between the subjective-vertical and sensed vectors, resulting in SMS. Since the subjective-vertical entails vectors from various sources, conflict incongruency happens in higher-order brain levels.

The absence of normal sensory inputs from otoliths compels other sensory inputs to determine spatial orientation, that may result in sensory conflict, SMS, or spatial disorientation (Kokhan et al. 2016). Attenuating one sensory system in contrast to the augmentation of another has also been proposed as the sensory compensation hypothesis. However, the lack of in-orbit evidence weakens this theory, as the severity of SMS differs among astronauts. Second, this theory does not answer specific mechanisms of other symptoms associated with SMS, such as vomiting. Lastly, it does not provide reasoning of SMS upon return to the Earth.

According to several neuro-vestibular studies, congruency of visual and vestibular stimuli is found to occur in the velocity storage of the vestibular system. The velocity storage is modulated by the vestibular-cerebellum mechanisms that store rotational information. Here, the velocity storage mechanism calibrates the eye velocity towards the spatial velocity during head rotation about the vertical axis and circular locomotion (Yakushin, Raphan, and Cohen 2017). This phenomenon allows the construction of the angular velocity of the head rotation in the CNS and enables gaze stabilisation through *vestibular-ocular reflex* (VOR); however, it is also prone to sensory noise or leak (Laurens and Angelaki 2011). VOR stabilises the eyes during the head rotation from the central vestibular network resisting eye movement to the opposite direction against the rotational movement at the corresponding velocity by the compensatory signalling mechanism of the extraocular muscles. VOR does not require light to be sensed and occurs through semicircular canals. Tracking moving objects is driven by the visual system and is only possible by the *optokinetic nystagmus* (OKN) reflex. OKN only occurs in light. However, the signal elicited continues in the dark, known as *optokinetic after nystagmus* (OKAN). Interestingly, VOR and OKAN have similar time constants, indicating that they both are processed in velocity storage (Yakushin, Raphan, and Cohen 2017). Vertical OKN and vertical VOR are significant in understanding their relevance in SMS as they both are influenced by otolithic inputs (Clément and Reschke 2008b).

On Earth, the linear VOR gains are 1, and their phases are 0. However, horizontal and vertical VOR gains decrease with a reversal of gain asymmetry only in the latter during the four days of spaceflight. The downward OKN gain is larger in space, and the reversal of gain asymmetry is also noticed. Interestingly, all gains return to pre-flight values within four to five days of spaceflight (Clément and Reschke 2008a; Oman, Pouliot, and Natapoff 1996). The horizontal VOR gain reduction did not contribute to motion sickness in ground studies (Clément and Reschke 2008b). However, it may be that the reversal of gain asymmetry and vertical gains reduction alter the ‘predefined’ velocity storage information, resulting in longer time constants to reconstruct the angular velocity concerning spatial vertical vector. The rationale behind this hypothesis is that the absence of gravity unloads the otoliths and therefore creates an imbalance of input convergence in the vestibular nuclei; thus, lower otolithic stimulation may

result in altered gains. Consequently, this may contribute to SMS (Nooij et al. 2017). The mechanism involving resetting the gains within four days of spaceflight is unknown, and further investigation is required to determine this aspect.

The sense of self in space alters due to microgravity. This suggests that otolith disturbance may disrupt spatial orientation (Chen et al. 2016). Consequently, spatial disorientation is another concern astronauts suffer during space missions. Spatial orientation provides the ability to navigate through environments, locate objects, and develop spatial memories (Colombo et al. 2017; Burgess 2006). Integration of auditory inputs, haptic feedback, visual inputs, vestibular system, and proprioceptive inputs provides meaningful information to perceive spatial orientation after processing in higher cortical areas (Clément and Reschke 2008b). The balance between the internal representation of the world and external position, motion, and orientation influences spatial orientation and is subsequently influenced by gravity. The brain's spatial frame of reference is either allocentric, object-to-object mapping or egocentric, subject-to-object mapping (figure 2.3) (Coughlan et al. 2018). Therefore, successful navigation, orientation, and goal-directed movements involve an optimal balance between both representations as common regions of brain activate in the bilateral front-parietal network (Zaehle et al. 2007; Adam et al. 2016). Both allocentric and egocentric representations are said to form a 'cognitive map' of the environment for humans to navigate and orientate (Ekstrom, Arnold, and Iaria 2014). In most situations, neither of the representations seems to be exclusively active.

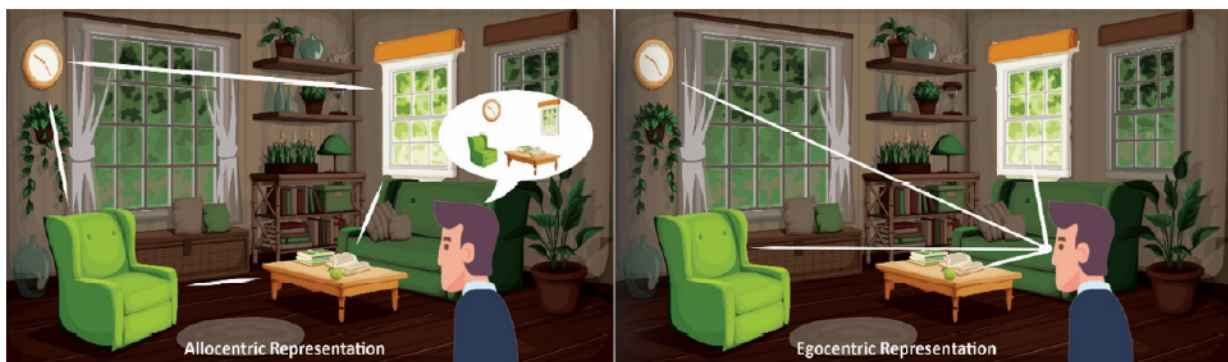


Figure 2.3: Illustration of allocentric and egocentric representation in the brain. Source: Parts of the figure has been sourced and modified from Shutterstock.com (Licensed stock illustration - 632432969).

Spatial orientation in space is believed to be dominated by an egocentric representation (Clement and Thu, 2013). Egocentric knowledge does not recruit hippocampal formations, the right in-

ferior and superior parietal cortex, and the bilateral ventral streams in contrast to allocentric processing (Zaehle et al. 2007). The inclusion of the hippocampus and its formation in allocentric processing intuitively signifies the contribution of place, grid, border, and head-direction cells. These cells form the GPS of the brain (Madl et al. 2015). This system enables object recognition in an environment alternatively known as the vision for perception (Adam et al. 2016). Place cells provide a sense of place that selectively fires in familiar locations of the environment independent of the person's orientation, and grid cells are located in the medial entorhinal cortex that provides cues for speed and direction, relaying spatial metrics to the hippocampus (Moser, Rowland, and Moser 2015). Head direction cells act as a compass of the human that fires at specific head directions, and the border cells only fire when individuals are near wall boundaries (Madl et al. 2015).

In contrast, egocentric processing strongly involves the precuneus region of the brain to enable visual-head-limb coordinated navigation and the basal ganglia for associating the reward mechanism in navigation (Madl et al. 2015) to promote goal-directed movements (Adam et al. 2016). This region in the left hemisphere is also involved in the mental stimulation of routes, suggesting its contribution to the egocentric representation (Zaehle et al. 2007). A recent study found that egocentric representation is strongly influenced by vestibular inputs that determine the body midline, and artificial stimulation to the system produces biased self-representation of the midline (Abekawa et al. 2018).

In space, the absence of the vertical vestibular cues may result in the gain of visual signals as compensation for the mismatch to match the 'normal' endolymph velocity more closely and estimate the rotational velocity more correctly by the velocity storage mechanism. However, this feedback becomes dependent upon the correct recognition of visual landmarks; therefore, the inability to recognise such landmarks may cause momentarily spatial disorientation. A recent study revealed that the spatial orientation of velocity storage aligned towards gravity-inertial acceleration in space and depended upon the subjective perception of each astronaut (Clément and Reschke 2018). The unloading of the otoliths in microgravity and the dominance of egocentric representation, together with the dependency upon subjective perception through visual cues followed by vestibular and proprioceptive cues, provide reasoning behind this shift and,

consequently, the risks of errors and bias increase, which may result in spatial disorientation.

The crux is that in space, the ‘normal’ and ‘Earth-adapted’ vestibular inputs are diminished due to the microgravity (particularly the vertical component of the otoliths). Therefore, the self-perception of up or down is absent, and the sense of motion, pressures, and orientation are altered. Long-term spatial disorientation occurs due to highly sophisticated alterations and adaptations in the brain that is concerning to the space crew members. Interestingly, similar to ageing patients, egocentric representation seems unaffected in contrast to a reduction of allocentric representation (Colombo et al. 2017). Therefore, similarities between ageing effects and brain adaptations due to microgravity should be compared. Researchers are attempting countermeasures such as implementing virtual reality, robotics, or skinsuits to reduce such effects in vision to increase space crew members’ safety, efficacy and performance.

The somatosensory system takes input from various receptors, including mechanoreceptors, proprioceptors, thermoreceptors, nociceptors, and chemoreceptors. These receptors are specialised for their function and provide relevant information to the brain through the central and peripheral nervous systems. The functioning of these receptors is crucial as the information gathered by these contributes to accurately perceiving a spatial orientation and communicating with the environment. Poor proprioception has been found in the elderly suffering from sarcopenia, known as muscle loss in the human body. In space, a concern is that astronauts also undergo muscle atrophy of the lower limbs, which notably may adversely affect proprioceptors. While astronauts must adapt to the altered sensory environment in space to maintain spatial orientation, muscle atrophy may make this adaptation more challenging because it can impair the somatosensory input that the brain relies on to maintain postural balance and spatial orientation. Therefore, the link between musculoskeletal deconditioning and neuro vestibular adverse effects is established through this understanding.

2.2.3 Musculoskeletal adverse effects of spaceflight

The human body evolves and adapts regularly under the influence of Earth’s gravitational pull to maintain homeostasis and smooth locomotion. In microgravity, astronauts undergo

muscle atrophy and bone resorption (Rupal et al. 2017). The duration of the space mission is a significant factor in the magnitude of these effects, with the first Skylab missions in 1975 revealing up to 11% muscle atrophy among astronauts (Lafevers et al. 1975). Observations in space missions suggest that muscle atrophy and bone resorption mainly occur in the lower limbs rather than the upper limbs (Rupal et al. 2017). Astronauts use upper limbs to navigate within the ISS; consequently, the lower limbs are less active, which may explain this phenomenon. However, other factors may contribute to muscle atrophy and bone resorption, such as radiation, nutritional, psychological stress, and hormonal fluctuations (Lee 2022). The implications of this phenomenon shed light on the complex and dynamic interplay between the human body and its environment, especially under extreme conditions such as space travel.

The majority of ground-based model studies, such as bed rest, limb immobilization, and water immersion experiments, indicated a prevalence of muscle atrophy (Narici and Boer 2011; Dirks et al. 2014). A recent study compared muscle atrophy in bed-rest control, exercise and ISS groups. The study found that the exercise group compared with the control group maintained muscle performance, whereas the latter had an approximate 10 % decrease in performance. LeBlanc et al. (1988) found a decrease of 12 % in muscle volume and 26 % in muscle strength of the calf planter flexors (soleus and gastrocnemius) in a 5-week bed-rest study on nine subjects. The dorsiflexion (tibialis and extensor longus) was not significantly affected. An MRI study on an 8-day space mission in the STS-47 Shuttle mission reported a 6.3 % decrease in soleus-gastrocnemius mass, an 8.3 % decrease in hamstring mass and a 10.3 % in lower back mass (Wall, Dirks, and Loon 2013), suggesting that muscle atrophy occurs even in very short spaceflights.

During a six-month spaceflight, Gopalakrishnan et al. (2010) found a muscle volume decrease in the calves of up to 16 %, followed by up to 24 % decrease in muscle strength of four crew members. The calves atrophied more than the thighs, with no detection of atrophy in the upper limbs. Another study found insignificant atrophy to the forearm muscles between the control and test subjects (Rittweger et al. 2005).

On Earth, the gastrocnemius and soleus are crucial for running, sprinting, walking, and pos-

tural balance. Neither of these movements are heavily required on the ISS, so these muscles are the most affected. Fitts et al. (2010) found that the soleus atrophied more than the gastrocnemius. Another study by Fitts et al. (2010) mainly studied the gastrocnemius and soleus of ten astronauts of the ISS between 2002 and 2005. The authors acquired muscle biopsies of these astronauts pre- and post-flight to monitor the structural and functional changes of the muscles. They found that the most affected muscle and loss of fibres were in the soleus type II, followed by soleus type I, gastrocnemius type II, and gastrocnemius type I.

Evidence shows that mechanical unloading due to microgravity prompts slow-to-fast fibre transition that inevitably decreases the population of type I fibres (Pette and Staron 2000). The same also suppresses protein synthesis and upregulates protein degradation pathways in the soleus greater than in the gastrocnemius resulting in more significant muscle atrophy in the former (Fitts et al. 2010). *Nitrogen oxide* (NO) is a vital signalling chemical that influences atrophy or contractility mediated by *neuronal nitric oxide synthases* (nNOS), and past research indicates that they are dependent upon skeletal activity (Powers and Jackson 2008; Copp et al. 2013). During endurance exercise, the nNOS binds to the *dystrophin-glycoprotein complex* (DGC) that produces NO and enables vasodilation to promote blood flow to the required muscles (Percival 2011; Finanger Hedderick et al. 2011). This also activates the ryanodine receptor that produces controlled calcium ions into the sarcolemma from the sarcoplasmic reticulum and is further pumped back in through active pump channels. However, reduced activity or mechanical unloading tends to downregulate nNOS expression and dislodges nNOS into the cytosol from the sarcolemma (Percival 2011). This negatively leaks calcium ions without being pumped back into the sarcoplasmic reticulum, prompting the activation of FoxO transcription factors. Both mechanisms induce muscle fatigue and atrophy, and FoxO-mediated pathways have been found to cause muscle atrophy in type II fibre more than the other fibre types (Wang and Pessin 2013).

Wolf's law suggests that mechanical loading promotes osteogenesis through mechanotransduction. Furthermore, bone remodelling is the balance between bone resorption and bone formation. This suggests a significant imbalance between both that leads to average bone loss. Given this understanding, a lack of compressive forces due to muscle atrophy may cause bone

resorption faster than formation. This may result in a net loss of bone mass. Therefore, bone resorption increases exponentially with muscle atrophy, not additively. Bone loss and muscle atrophy are closely intertwined.

In space crews, bone resorption is a more severe and problematic condition. As with muscle atrophy, bone resorption is more prevalent in the lower and upper limbs. In early space missions, bone loss occurs between 1.0 % and 1.5 % per month, despite countermeasures, compared to postmenopausal or elderly women, which is 1.0 % per year (Orwoll et al. 2013). LeBlanc et al. (2000) found that bone resorption of the trabecular bone of the hip occurred at a dangerous 2.2 % per month. Therefore, space missions longer than six months and those with deeper space expeditions have an increased risk of osteoporosis or osteopenia (Bloomfield 2010).

Although bone loss has been observed in space, skull bone formation is attributed to a unique set of factors. Unlike weight-bearing bones in the lower body, the skull is not subjected to the same gravitational forces, which does not result in the same rate of resorption as the lower body bones. Furthermore, the skull acts as a shell to protect the brain. Additionally, fluid shifts may stimulate bone formation in the skull due to higher intracranial pressures in microgravity.

These findings demonstrate the complexity of the human body's response to microgravity and the need for continued research to understand the mechanisms involved. Nonetheless, it is clear that the fluid shift-related physiological adaptations in space profoundly impact human physiology and require careful consideration in developing strategies to mitigate the effects of space travel on the human body. Muscle atrophy and bone resorption may also affect space crew members performing EVA, such as moonwalking, as the reduction of muscle strength, mass, and bone strength inevitably makes them fatigue quicker.

Astronauts also experience a unique physiological phenomenon known as *space adaptive back pain* (SABP), which is attributed to spinal lengthening that occurs within the first few days in orbit. A retrospective study by Kerstman et al. (2012) found in 726 astronauts that at least 50 % of astronauts complain of back pain, with 86 % experiencing pain primarily in the lumbar back. The spine is subject to constant compressive loads on Earth due to gravity. However, the absence of gravity in space results in decreased curvature and heightened and increased

fluid volume of the *inter-vertebral discs* (IVD), causing spinal elongation. The diminished compressive loads may disrupt hydrostatic fluid equilibrium, causing lesser fluid outflow from the nucleus pulposus into the circulation. Interestingly, similar effects have been observed during supine bed rest. The IVD nucleus pulposus is avascular and lacks innervation, so forced convection and internal compressive loads primarily maintain fluid equilibrium. Hence, astronauts tend to find relief by adopting a 'fetal tuck' position, bringing their knees towards their chest. This position may increase intra-discal pressures forcing the fluid outwards from the nucleus pulposus toward the end plates and, subsequently, into the human blood circulation, causing compression of the spine.

A recent study by Wu et al. (2023) modelled mechanical changes of the lumbar spine in Earth's gravity and microgravity and compared this to a model of the spine in a fetal tuck position. They found that the fetal position reversed microgravity-induced changes in the lumbar spine and caused equal or larger compression forces of Earth's gravity. This position may result in mechanical contraction of the spine flexors. In addition to this, Sayson et al. (2013) proposed that this position may activate type I and II mechanoreceptors resulting in a natural human response in inhibiting pain by releasing natural opioids and neutralising substance P in the spinal cord, as well as reducing type IV mechanoreceptor activity, which is more sensitive to injury pain perception. Hence, atrophy in the lumbar paraspinal muscles may also cause neuromuscular abnormalities (Chang et al. 2016).

A long-term risk that astronauts may encounter is *herniated nucleus pulposus* (HNP), also known as a slipped disc. The risk of developing HNP in astronauts occurs upon their return to the gravitational forces on Earth (Belavy et al. 2016). Microgravity induces a decompressive state in astronauts that leads to spinal elongation, increasing the risk of HNP (Sayson et al. 2013). Upon return to Earth, the IVD of the astronaut may suffer excessive strain and stress, causing the nucleus pulposus to protrude through a tear or rupture in the annulus fibrosus. Consequently, as space members return to Earth, they have complications in performing natural gait that prompts them to undergo rehabilitation and to some extent, require assistive technology.

2.2.4 Countermeasures in Space - A Brief

In light of the physiological adaptations, extensive research is necessary, as well as the development of effective countermeasures for physiological deconditioning to enable long-term space travel and habitation safe (Fitts et al. 2010). Multiple countermeasure strategies exist, which includes a combination of aerobic and resistive exercises (Petersen et al. 2016).

As a countermeasure to musculoskeletal deconditioning, treadmill or flywheel exercises in early space missions reduced muscle atrophy; however, at the end of a three-month mission, muscle strength was still lost by ten percent (Thornton and Bonato 2013). Therefore, aerobic exercise cannot mitigate muscle atrophy alone, and resistance exercise is an essential countermeasure. Space crew members were initially provided with an *Interim Resistance Exercise Device* (IRED) to perform these exercises in space. Exercise in IRED improved muscle strength and volume, but bone resorption still occurred. The IRED was limited in supporting a wider range of exercises. Furthermore, exercise protocols in the IRED provided resistance during a concentric contraction but cannot offer sufficient resistance during an eccentric contraction. Due to this, eccentric exercises (Schneider et al. 2003) were challenging in space. Attempts to increase resistance in IRED led to higher injury rates, and resistance selection was challenging with only 140-kg resistance available (Schneider et al. 2003).

Consequently, *Advanced resistance exercise device* (ARED) was introduced in 2008, which enabled users to perform all sorts of exercises, such as squats and calf raises. This device provided resistance to up to 250 kg. Compared with IRED, ARED allows participants to vary their stance width and maintain a stable and constant load. This has enabled it to produce superior results (Smith et al. 2012), rendering IRED obsolete (Lang et al. 2017). In space, high-intensity resistive exercise in ARED significantly reduced bone resorption in a long-duration spaceflight mission (English et al. 2015). However, ARED exclusive use does not mitigate microgravity-induced effects. With the addition of alendronate, an antiresorptive drug, ARED has shown a remarkable reduction in bone loss and improved muscle strength and volume (LeBlanc et al. 2015). Whether long-term drug use has a negative impact remains uncertain. ARED use has also increased the risk of impaired visual acuity (Hargens, Bhattacharya, and

Schneider 2013), another research focus of space agencies; therefore, it may be limited for a long time.

Exercise performed during spaceflight can further help maintain neuromuscular and cardiovascular functions and reduce functional performance declines (Mulavara et al. 2018). Ground-based studies also provided similar results for subjects who participated in exercise groups. Humans suffering from OI on Earth commonly engage in endurance exercises to improve OI symptoms (Winker et al. 2005). Furthermore, astronauts in space also seem to experience better tolerance to OI when performing rigorous exercises during space missions (Lee et al. 2010). Based on these observations, effective countermeasures can reduce physiological deconditioning.

Other devices are being researched, such as *functional resistive exercise devices* (FRED) (Weber et al. 2017) to reduce muscle atrophy of the paraspinal muscles or treadmill vibration isolation systems to prevent muscle atrophy. While the ARED or other devices show promise in reducing physiological adaptations, preparation for exercise on these devices can be time-consuming. As a result, this disadvantage may negatively impact performance and reduce the time availability for missions (Loehr et al. 2015). Additionally, the device's weight may pose structural issues for the spacecraft and regular maintenance is necessary due to mechanical failures. The design of future spacecraft is expected to be much smaller in size and capacity, such as the ORION spacecraft, and therefore, the ARED or other bulky devices may not be able to fit because of space limitations.

A promising alternative is emerging to address these challenges through exoskeletons, wearable devices that attach to the limb of the user, providing assistance or resistance during physical activities and rehabilitation. Their portability and versatility make them ideal for use in multiple settings, including space, and they are designed to be compliant, thereby reducing injury risks. In recent years, NASA has been researching exoskeletons for space crew members to be able to perform assistive and resistance exercises, which is discussed below.

2.3 A Summary of Current Lower Limb Exoskeletons and Soft Exosuits

There are three broad categories of exoskeletons, including those that enhance performance, therapeutic benefit, and assistive function (Young and Ferris 2017). The first category aims to improve performance in the industry setting, military missions, or as a general tool for carrying heavy loads beyond the strength of the individual. Medically relevant interventions are the focus of therapeutic and assistive exoskeletons. The former aims to increase muscle strength, agility or endurance of weakened muscle groups due to disease or injury and to eventually become independent from using the device. By assisting patients who are paralyzed by a stroke or spinal cord injury, the latter aims to help them improve their mobility and independence (Young and Ferris 2017). In either case, assist or resist can be used.

According to Rupal et al. (2017) of the current lower limb exoskeletons, only a few are available commercially today despite at least 25 assistive devices, seven therapeutic devices, and twenty performance-enhancing devices. The number of exoskeletons for lower limbs is much higher than for upper limbs (Gopura et al. 2016) since this review focuses only on lower limbs. However, only a few exoskeletons enable muscle strengthening and resistance training. One of those devices, designed by NASA, provides resistance training to astronauts as part of its NASA X1 robotic exoskeleton (Rea et al. 2013).

In the NASA X1 exoskeleton (figure 2.4 a), four active DOF are combined with six passive DOFs for abduction/adduction, internal/external rotation, and dorsiflexion/plantarflexion, and it is worn around the lower limbs through cuffs and a waist belt (Rea et al. 2013). The exoskeleton could be adjusted as per the user's measurements by adjusting the adjustment points. Since the exoskeleton is primarily designed for resistance training, portability and compactness are its highest priorities, eventually replacing the ARED. There are features on the exoskeleton that enable eccentric and concentric exercises in spaceflight. Eccentric contractions occur when muscles are lengthened under load after being shortened. The eccentric action, which transmits resistance during the eccentric action, enables muscle hypertrophy, which is more

effective for muscle strengthening and gain (Farthing and Chilibeck 2003). NASA X1 Exoskeleton transmits torques of 300 Nm or more at each joint, allowing coordinated exercises such as straight-dead lifts. The joints in this exoskeleton are controlled by rotary series elastic actuators paired with custom motor controllers.

He et al. (2014) further modified the NASA X1 exoskeleton by integrating it with neuro-robotic interfaces for stroke rehabilitation (figure 2.4 b). By integrating *Electroencephalogram* (EEG) and *Electromyography* (EMG), the authors aimed to achieve joint kinematic decoding. They aimed to provide assistance rather than resistance to the user. According to the authors, the head-shift artefacts may have contaminated EEG signals, and the latter may have had low accuracy due to placement shifts of the EMGs. Thus, research is underway to develop robust algorithms to minimise these effects.

An exoskeleton designed by Washabaugh et al. (2021) is equipped with an elastic mechanism that resists flexion and extension in one degree of motion (figure 2.4 c). Each nylon-coated subassembly contains a compression spring inside a cylinder as well as a plunger, which compresses the spring as the cable is pulled. It was equipped with a ball and shank at the bottom end. A quick-release mechanism was used to attach the fitting to a point on the edge of the pulley in the end cap of the cylinder. Choosing the angle at which the spring is not compressed was determined by a clutch mechanism in the pulley, and ratchet gears were fixed to the device joint, pawls, and ratchet springs. As the detent was retracted, the ratchet spring ensured that the pawl was engaged with the ratchet gear. When the clutch is engaged, the pulley rotates along with the user's joint, pulling the cable and compressing the spring. This configuration provides resistance by rotating along with the user's joint. Disengaging the clutch will remove resistance from the system.

While walking, a range of levels of targeted resistance were provided to the user, and the authors observed a greater activation of knee flexion and extension muscles when resistance was applied. As a result of removing the resistance, joint angles and foot clearance increased. In particular, an increase in plantarflexion and knee extension was observed during the stance phase and longer step lengths. Similarly, the swing phase exhibited greater dorsiflexion, hip

flexion, and knee flexion (Washabaugh et al. 2021).

Conner et al. (2020) developed exoskeletons to assist children with cerebral palsy in rehabilitation (figure 2.4 d). Conventional rehabilitation has been unable to improve the gait significantly. According to the authors, the rehabilitation approach was too generic and not targeted enough. The exoskeleton included calf straps and foot insoles connected via a steel cable. Its primary purpose was to increase the engagement of the plantar flexors during push-off and respond to the user's movement. Sensors were installed in the foot insoles so the resistance could be adjusted based on ankle joint angles and moments. While walking, the authors found an improved activation of the plantar flexors, which reduced anterior tibialis activity, reducing co-contraction. The authors wanted to reduce muscle co-contraction among cerebral palsy patients since this results in higher metabolic costs. Resistance exercise through exoskeletons provides long-term therapeutic effects, as opposed to assistance provided by assistive exoskeletons. A similar observation was made with the CaLT exoskeleton (Wu et al. 2011), which compared resistance and assistance exercises for people suffering from spinal cord injuries using this exoskeleton. It was observed that the former has better rehabilitation and therapeutic effects and higher performance than the latter.

Although many potential users have accepted hard exoskeletons, translation from research to clinical use or home use has been difficult since these devices are bulky and heavy due to their rigid structure. Furthermore, there are safety regulations, compliance issues, and cost implications. Exoskeletons that rely on rigid components are a constraint since they reduce the range of motion of a human's natural gait or movement. Additionally, this disadvantage increases the risk of sustaining injuries, swellings, or fractures, mainly due to the rigid frames and straps that result in excess pressures (Gorgey 2018).

Hard exoskeletons require more power and must be recharged more frequently due to their inertia and control strategies. Researchers are developing lighter products and batteries to increase power efficiency, particularly concerning human and exoskeleton interactions (Rupal et al. 2017; Young and Ferris 2017). Rigid exoskeletons are challenging to fit, train, and adjust. Similar to current commercial exoskeletons such as ReWalk, it takes a few sessions to acclimate



Figure 2.4: Various exoskeletons in research. (a) The X1 Exoskeleton. Designed by NASA in partnership (Rea et al. 2013) (b) Modified X1 Exoskeleton (He et al. 2014) (c) Exoskeleton designed by (Washabaugh et al. 2021) (d) Exosuit designed by (Conner, Luque, and Lerner 2020) (e) Exosuit by (Quinlivan et al. 2017) (f) Exosuit by (S. Lee et al. 2018) (g) Exosuit by (Bartenbach et al. 2015) (h) Exosuit by (Sridar et al. 2017), (i) Myosuit by (Schmidt et al. 2017) (j) Exosuit by (Awad, Esquenazi, et al. 2020) (k) XoSoft by (Natali et al. 2019) (l) Modified XoSoft by (Di Natali et al. 2021)

to them. Additionally, ambulation in rough terrain or adverse weather is not possible with current available ambulatory exoskeletons. This prompts a need for lightweight, compliant, soft devices that reduce joint misalignment.

In concept, exoskeletons enable and assist desired tasks by being worn over the body. These devices' future success and trend will be determined by their ability to be lighter, cheaper, softer, and, most importantly, well suitable for the human body. Those are the principles of soft exosuits. In a recent review of soft lower limb exosuits, Khomami and Najafi (2021) found six exosuits used for power augmentation and 15 for rehabilitation. In general, most of the exosuits designed and in research are thus focused on assistance rather than resistance; however, it is crucial to review some of them to understand the design requirements better. The following criteria were required of papers included in this research:

- The wearable device uses soft materials.
- The wearable device is for rehabilitation or assistance for the lower-limbs only.
- The wearable device uses cables or soft materials for actuation transmission.
- The wearable device uses conventional or novel actuation methods.
- The wearable device must not include rigid parts for actuation transmission.

In order to assist people with ankle plantarflexion and hip flexion, the Conor Walsh group has developed a variety of exosuit versions (Quinlivan et al. 2017) (figure 2.4 e). It has straps around the calves and a waist belt connected to vertical straps. To increase stiffness and facilitate force transmission through the vertical straps (Asbeck et al. 2014), webbing is used to reinforce them. The exosuit is controlled by Bowden cables at the foot anchor points, as well as distal and posterior calve straps (see figure 2). Toe-rise activation occurs in the stance phase when the exosuit contracts and assists with plantarflexion for the swing phase (Quinlivan et al. 2017). Currently, this exosuit is actuated by geared motors. Since the load path passes through the knee joint centre, joint moments around the knee are prevented. A unilateral design of a soft exosuit for stroke patients improved their mobility when used with a paretic limb. Compared to gait without the soft exosuit (Awad et al. 2017), interlimb asymmetry was decreased

by 20 %, and the metabolic cost was reduced by 20 %. However, the experiment was conducted in a controlled treadmill environment and with selection criteria for participants. Furthermore, long-term unsupervised use of this exosuit is uncertain and careful pressure measurements are necessary within the strap regions to prevent ischemia.

The same research group has further reinforced this design by including a hip extension feature by introducing thigh straps (Lee et al. 2018) (figure 2.4 f). Figure 2.4 f also shows the actuator system consisting of four single units (two for hip extension and two for multi-articular units) that pull the inner cable respectively upon actuation. It weighs 5.1 kg and is attached to the lumbar region. Carrying a backpack load influences gait, and hip and trunk range of motion, increasing step width variability (Qu and Yeo 2011). Increased step width variability increases the risk of falls. Therefore, it may not be suitable for the elderly to carry such actuation devices in their backpack in a long-term scenario; however, this design is helpful as an assistive performance augmentative device. It has minimised metabolic cost by an average of 12.1 %, an indicator of assistance successfully (Lee et al. 2018).

Similarly, Bartenbach et al. (2015) proposed a soft exosuit that is actuated with cables to restore mobility and gait (figure 2.4 g). Two anchors are located at the hip and the shank to support the webbing segments. In order to provide adequate torques at the hip and knee joints, the knee cap supports routing from the lower shank to the posterior waist belt at the hip. On actuation, the cables pull the webbing segments together and transfer tension forces to the anchor points. A linear actuator was used per leg for multiple joint combinations for simplicity. The authors placed anchor points and routed webbing to either support flexion or extension. However, one actuation for a series of joints results in movement coupling, so independent joint movements are not possible. Accordingly, the authors used a set of algorithms to determine the optimal joint combination to maximize the amount of work required during the desired motion for anchor point placement (Bartenbach et al. 2015). As a result of the study, hip and knee extensions were found to give optimal results during sit-to-stand manoeuvres, resulting in the prototype design shown in (figure 2.4 g). This concept is intended for individuals with gait impairment who can walk with some support device, such as crutches, as a means of walking. As well as providing support during sit-to-stand movements, the exosuit is intended to be worn

by people while using a wheelchair.

Sridar et al. (2017) recently developed a soft-inflatable exosuit (figure 2.4 h) to rehabilitate stroke patients. Two pockets of actuators in the exosuit are attached to an elastic knee sleeve and tightened with adjustable straps. The electro-pneumatic actuators were designed based on beam mechanics, and the I beam generated greater force than the O beam. Based on the ratio of femur and tibia bones, the actuators were sized accordingly. This exosuit is made of neoprene, a fibre that conforms smoothly to the shape of the knee and weighs 160 grams in total, including the electronics. It is equipped with two force sensors embedded in the insole that communicate toe-off and heel force to the knee exosuit's microcontroller. From mid-stance to final swing phases, this exosuit assists with gait.

Sridar et al. (2017) examined its effectiveness by measuring the rectus femoris muscles using *Surface Electromyography* (sEMG) over a treadmill instead of measuring metabolic costs using coulometry. As a result of the reduction in muscle signals, the exosuit is effective as it indicates less muscle recruitment during locomotion. However, the research group only measured the quadriceps muscles, so additional measurements are required to assess their effectiveness. Because this rehabilitation regime relies on motion cameras for calculating joint angles and kinematics, it cannot be applied in a clinical setting. Therefore, portability is not possible.

Schmidt et al. (2017) designed an exosuit called Myosuit to assist individuals with mobility impairments (figure 2.4 i). It weighs almost five kg and is made from soft, flexible materials, making it comfortable and unobtrusive to wear. The Myosuit works with the wearer's muscles using sensors and actuators. It is a bio-inspired three-layer architecture that uses the concept of structural, passive and active support similar to bone, ligaments, and muscles, respectively. The active layer consists of artificial tendons guided through teflon pipes that initiate from the back of the hip to the front of the ankle and are anchored through the foot wraps. The control units are attached to the waist. Two sets of rubber bands are attached from the frontal hip to the knee to aid hip flexion and the back of the knee to the ankle to aid knee flexion. The control strategies include gravity synergy to improve gait movements and anti-gravity with compensation to assist in anti-gravity movements such as sit-to-stand. Those with

mobility impairments, such as neuromuscular disorders or age-related muscle weakness, can benefit from the myosuit's improved mobility and quality of life. Hauff et al. (2020) demonstrated the effectiveness of the Myosuit on real subjects by reducing muscle activity when walking and climbing stairs, resulting in reduced fatigue and improved gait. Based on the results of this study, it is clear that the Myosuit exosuit can positively impact the lives of people with mobility limitations.

Restore ReWalk (Awad et al. 2020), a commercially available exosuit, was available for stroke rehabilitation in 2019 (figure 2.4 j). In order to improve gait symmetry, this device assisted with ground propulsion and clearance during plantarflexion and dorsiflexion to increase clearance from the ground. As a result, users were provided with 'targeted assistance' for rehabilitation, resulting in a gradual improvement in their gait, walking speed, and posture without using this exosuit. A multi-site clinical trial was conducted in 2020 to evaluate the safety, reliability, and feasibility of the *ReStoreTM* device in post-stroke gait rehabilitation. During the study, 44 participants were trained on the device for up to five days (Awad, Esque-nazi, et al. 2020). The study's results confirmed the device's safety and reliability when used under a physical therapist's supervision. Furthermore, the study reported that device-assisted and unassisted maximum walking speeds increased after only five days of walking practice with the device, regardless of the participants' use of other assistive devices.

Studies also focus on developing pneumatically controlled soft orthotics to help people with drop feet walk better. As a result, there is a growing interest in developing soft exosuits as assistive, therapeutic, and performance-enhancing devices. An EU project called XoSoft is currently developing assistive soft exosuits for lower limbs to encourage researchers to develop them to improve quality of life, immobility and ADLs (Ortiz et al. 2017) by using a user-centred design strategy. Natali et al. (2019) designed a XoSoft beta exosuit that provides assistance in different gait phases for stroke patients who have paretic legs (figure 2.4 k). A backpack containing an electromagnetic clutch and CPU connects the calf and thigh straps with bowden cables. By supporting the knees and hips, the exosuit enhances gait symmetry and provides an improved range of motion.

Determining the optimal actuation control and power requirements for soft robotics without rigid frames is difficult. It is also challenging to transmit large forces. Therefore, providing high-resistance training to the elderly, people with gait disabilities, or space crew members to promote PRT and prevent muscle atrophy and bone resorption is difficult with soft exosuits. Hansen et al. (2009), however, found that continuous low to moderate-intensity exercise produces similar results to short high-intensity exercises. Di-Natali et al. (2021) modified the XoSoft exosuit to provide resistance rather than assistance to counteract psychological adaptations in space by using resistance rather than assistance (figure 2.4 1). As part of the modification, resistance will be added during normal daily activities, as well as knee flexion and extension actuation units. Furthermore, A soft sensor embedded in a knee brace measures the angular displacement at the knees of the exosuit. The sensor is sensitive to strain and pressure due to knee bending. In certain circumstances, such as accidental contact with the surroundings, it is essential to distinguish strain from pressure simultaneously. Wearing the knee brace under the exosuit directly measures the strain induced by knee bending. A sensor also provides the gait phase, so the resistance required for the target muscle can be calculated. The finite state machine control strategy of this modified exosuit is that resistive forces are applied against the movement to engage the agonist muscles more, resulting in higher muscle activation and eventually, effort (Di-Natali et al. 2021).

Swaminathan et al. (2021) developed a new ankle exosuit to increase planter flexor effort during stance for stroke patients. The calf strap is created using Fabrifoam, which combines a nylon/spandex layer with a high elastic polyurethane and a third layer of polyether-polyurethane open foam to prevent slippage. Bowden cables are attached to the calf straps. There are two anchor points in the exosuit: one at the front of the shin and one at the top of the shoe. With one degree of flexibility, the exosuit resists plantarflexion when the user takes a late stance. It weighs around 4 kilograms, including the waist belt, actuators, and cables. According to the authors, this approach provided ‘targeted’ resistance to the subject at certain phases or times, and they found increased plantarflexion activity and soleus activity. This exosuit was developed by keeping in mind a study that found stroke patients improved stride length symmetry by using stance or swing resistance during those phases (Swaminathan et al. 2021). The bio-

logical ankle torque and soleus muscle activity increased at all levels of resistance force when the exosuit applied targeted resistance at the ankle joint. Upon removal of resistance from the exosuit, the peak plantarflexion angle was higher than the baseline, further demonstrating the therapeutic effect of the exosuit.

2.4 Actuation Methods and Shape Memory Materials

In most cases, exosuits operate using conventional actuation methods such as pneumatic or electrical cable-driven, depending on the force required. Exoskeletons and exosuits employ a variety of actuators (figure 2.5). A hydraulic actuator is not recommended for soft exosuits since it lacks precision, involves a risk of liquid leakage, and is bulky in size. Consequently, hydraulic actuators are primarily used in large robotic systems or rigid exoskeletons, such as in BLEEK (Rupal et al. 2017). A pneumatic actuator actuates through compressed gases, such as air, through a pneumatic source. Their power-to-weight ratio is less than hydraulic actuators but greater than electric actuators. As they require less pressure to operate than hydraulic actuators, they are less susceptible to contamination, non-inflammable and less susceptible to contamination. Electric actuation is the most common form for rigid and soft exoskeletons (Frisoli 2018). Electric actuators make portability possible as devices can be made smaller and less bulky. Despite being the safest, electric actuators have the lowest power-to-weight ratio compared to hydraulic and pneumatic actuators. Table 2.1 summarizes the differences between these conventional actuation methods.

In designing exoskeletons and exosuits, several power transmission methods are adopted for the use of electric actuators (Frisoli 2018). These include gear-driven, cable-driven, *series elastic actuators* (SEA), and variable impedance actuation. SEA is a method of addressing the high impedance inherent characteristic of electric DC/AC actuators. The SEA consists of motors connected to a gearbox and an elastic component, such as a spring. Adding an elastic component to the spring improves force control since force output and spring lengths are directly proportional (Kooij et al. 2006). This improves its tolerance to load, compliance, and mechanical impedance (Leal Junior, De Andrade, and Filho 2016). The SEA has a limited

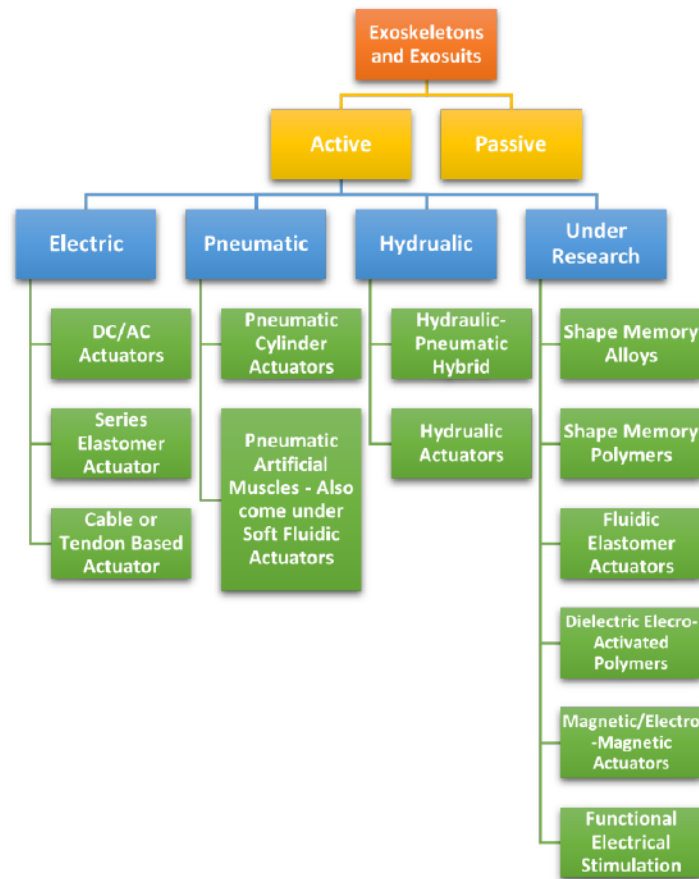


Figure 2.5: Actuators in exoskeletons and exosuits.

Table 2.1: Comparison of Hydraulic, Pneumatic, and Electric Actuators

	Hydraulic	Pneumatic	Electric
Operation Method	Large pumps with regulators, motors and filters	Compressor with controls, filters and valves	DC/AC using power amplifiers and coolers
Power-to-weight ratio	High	Medium	Low
Power Efficiency	Approx. 50 – 60 %	Approx. 20-30 %	Approx. 80 – 90 %
Principle of Power	Pressure – Oil and Additives	Pressure – Air	Electricity and Cables
Safety	Fluid leakage could cause potential fire risks and contamination	Risk of ruptures can cause severe damages	High safety provided enough insulation and grounding
Use in Exoskeletons or Soft Exosuits	Least	Many	Most

bandwidth and stiffness (Vallery et al. 2008), despite its advantages.

Soft exosuits and rigid exoskeletons tend to utilize cable-based actuation since motors and actuators are difficult to mount on soft textile fabrics. As motors and joints are separated, exosuits and exoskeletons may be improved in design. For example, all motors could be located in a backpack (Frisoli 2018). This type of actuation is sometimes referred to as tendon-driven actuation. A Bowden cable is a natural choice for such actuation as the inner cable is fixed in length and attached to pulleys inserted into the outer sheath. Many researchers have used this actuation method, including Bartenbach et al. (2015), Asbeck et al. (2014), Xiloyannis et al. (2017), and Wie et al. (2018). Bowden cables have provided promising results regarding back-drivability and force transfer, which is rapidly becoming a preferred method of actuation (Frisoli 2018; Wei et al. 2018).

In the past, studies have attempted to develop soft pneumatic actuators. Inspired by muscle physiology, pneumatic actuators have given rise to *McKibben pneumatic artificial muscles* (PAM). Upon pressurization, the PAMs expand radially and shorten longitudinally, mimicking the same action of muscles. An inflatable inlet elastic tube, which imposes a geometrical constraint, is covered by a non-extensible yet flexible braided shell that allows the tube to be contracted only when compressed (Volder, Moers, and Reynaerts 2011). Based on their compliance and improved power-to-weight ratio, Tsagarakis, Caldwell, and Medrano-Cerda (1999) developed a seven-degree exoskeleton using PAMs in 1999. Beyl et al. (2011) developed an exoskeleton that used PAMs to support knee extension/flexion as an agonist-antagonist pair. Chambers, Carignan, and Wereley (2016) recently investigated the feasibility of integrating PAMs with FORTIS to support torques at the knee joints. Rigid parts are necessary at the ends of the PAM to prevent air leaks, which can be large. However, research is being conducted on developing miniature yet multifilament PAMs and softer systems.

The concept of exosuits as assistive devices is that they could be worn as regular daily clothing. The exosuits use conventional methods of actuation, which typically consist of rigid parts, making them inaccessible to weaving into the clothing due to the difference in stiffness. Although cable-based actuation has shown some optimism in achieving this, shape-memory materials for

actuation are a relatively new field of research that could provide a solution.

A *shape memory alloy* (SMA) is a soft actuator that contracts upon heating with ohmic or water above the phase-transformation temperature and then returns to its original form when cooled (Mavroidis, Pfeiffer, and Mosley 1999). When heat or stress is applied, the crystalline structure changes from a soft phase, martensite, to a hard phase, austenite, which occurs at high temperatures. In this case, the stiffness varies from 80 to 30-40 GPa upon phase transformation respectively. Several shape memory alloys are based on iron, copper or nickel. However, nitinol, a nickel-titanium alloy, is the most commonly used. Nitinol is highly flexible, recoverable and stable during transformation compared to other materials. The strain produced by one wire of nitinol is approximately 8 %. However, different combinations produce different strain percentages at the expense of force (Mavroidis, Pfeiffer, and Mosley 1999; Dynally Inc. and Flexinol® n.d.).

Even though nitinol actuators offer advantages such as being less noisy, lightweight, compact, and having a very high power-to-weight ratio, they have limited bandwidth and require significant cooling times. Different diameters of the wires produce higher forces of up to 30 N at the expense of higher power requirements due to reduced resistance and longer cooling times (Dynally Inc. and Flexinol® n.d.). Nitinol wires of 0.31 mm and 0.10 mm, for example, have resistances of 12.2 Ohms/m and 126 Ohms/m, and have forces of 1.4 and 12.5 N. However, cooling times are 8.1 seconds and 1.1 seconds, respectively. The possibility of overheating can also be a concern if heat dissipation methods are inadequate. For example, a 0.51 mm actuator could take up to 16 seconds to cool after contraction. Moreover, SMA actuators are non-linear due to hysteresis, which can hinder control precision (Copaci et al. 2017).

Few researchers are exploring using SMA actuators as an alternative to conventional methods. Copaci et al. (2017) have placed three 0.51 mm nitinol wires inside a *Polytetrafluoroethylene* (PTFE) cable covered in a Bowden sheath to assist in elbow and shoulder rehabilitation. Additionally, they have created control mechanisms for SMA actuation that prevent overheating and pulley-based looping from achieving displacements over 20 % (Vil-loslada et al. 2015). Yang et al. (2015) developed a tendon-driven hand exoskeleton using

SMA springs for finger joint rehabilitation. While there has been interest in using SMA in exoskeletons, little is known about its use in exosuits.

Another promising actuator for exoskeletons and exosuits is *shape memory polymers* (SMP). A study by Haines et al. (2014) found that twisting insertion into fishing lines (nylon 6,6) with a weight attached at the distal end eventually formed coils. A constant rotation occurs on the proximal side, which is fixed. Excessive weight can break nylon fibres, while underweight can cause them to snarl during twisting. Since the fibres have a negative thermal coefficient, these contract upon thermal heating, producing a stroke of as much as 49 %, which can lift muscles more significantly than those of comparable dimensions. In general, contraction occurs between 40° and 60° degrees of heating and continues with higher temperatures. This type of actuator is characterized by non-hysteresis characteristics, but friction-based hysteresis can occur (Haines et al. 2014; Haines et al. 2016). Previously, carbon nanotube yarns were explored and displayed stroke lengths of at least 30 to 50 %; however, the fabrication cost prevented further exploration of this material (Haines et al. 2016). The *twisted coil actuators* TCAs used on fishing lines are non-conductive. Thus, researchers have developed silver-coated fishing lines or other conductive materials that can be integrated with TCAs to make them conductive. Various researchers have integrated SMA with SMP for two reasons: firstly, as a heat source, and secondly, to provide two-way actuation.

A number of researchers are interested in fishing line actuators and explored these in greater depth for exosuit and exoskeleton applications (Cho et al. 2016; Tang et al. 2019; Park et al. 2017). This TCA has a limited bandwidth lower than SPA (figure 2.6). However, the bandwidth has improved when it is used in forced air or helium, indicating that the bandwidth depends on the environment.

In a study by Zhang et al. (2019), several different actuators are compared about linearity, strain, bandwidth, power density, and efficiency. The TCA and SMA are associated with high power density and similar strain values compared to skeletal muscle, but they also exhibit low bandwidths and inefficiency. TCA has a 25 percent higher linearity than SMA. The performance and properties of TCA are closer to those of skeletal muscle compared to those of SMA, and

robust control methods are necessary to improve their functions.

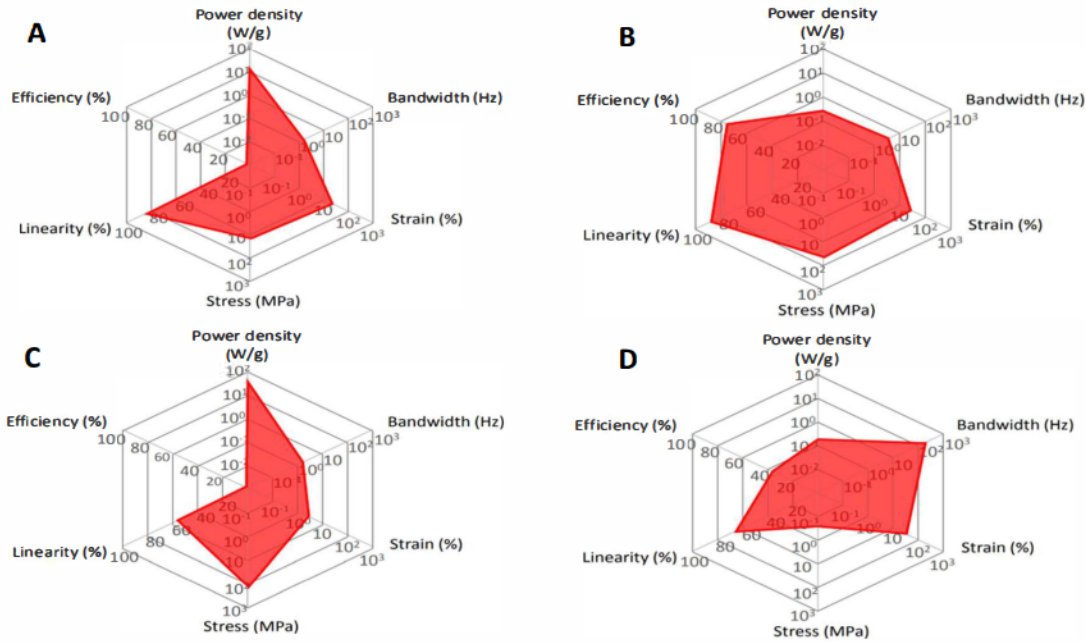


Figure 2.6: Property comparison between different actuators and skeletal muscle **A)** Twisted and Coiled Actuator **B)** Twisted Actuator **C)** Shape Memory Alloy **D)** Skeletal Muscle. Adapted by Zhang et al. (2019)

TCA is relatively new, and improvements in its function are inevitable with research. Cho, Song, S. Y. Yang, et al. (2017) compared nylon TCA with spandex TCA and found that the latter showed improved strain and acted at lower temperatures. A bundle of TCA fibres has also been suggested to increase force output. Further, polymers used for TCA are commonly used for clothing, allowing them to be seamlessly woven into clothing. Research on soft exosuits has not yet utilized TCA; therefore, this is an area of promising research.

The arrangement of actuators also influences their properties and may improve their function. One of the arrangements relevant to this study is a bio-inspired pennate actuator modelled after muscle fibre arrangement. Skeletal muscles have muscle fascicles that attach to tendons and the line of action obliquely. The fascicles may be arranged in parallel, circular or convergent arrangements, such as unipennate, bipennate, or multi-pennate (figure 2.7).

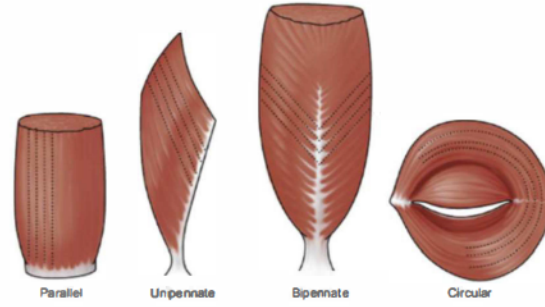


Figure 2.7: Various muscle architecture of human body (Carlson et al. 2019)

The pennate arrangement enables incorporation of an increased number of fascicles than the parallel arrangement, as the former has a higher *physiological cross-sectional area* (PCSA). PCSA is the area perpendicular to each muscle fibre [Muscle Biology]. Subsequently, the pennate architecture generates greater force at the cost of lesser contraction velocity and displacement than parallel muscles.

Azizi et al. (2008) describe this pennate architecture as a variable gearing phenomenon. As muscles contract, they shorten and rotate to increase the pennation angle. Since each rotating fibre reduces its velocity while it rotates, the line of action of that muscle has a higher velocity than the individual fibres. As an individual fibre moves, an *architectural gear ratio* (AGR) indicates the velocity amplification effect, which is greater than 1. Jenkins and Bryant (2019) developed an actuator with variable stiffness by modelling a bipennate muscle with twelve fibres of 7.6 cm each and a pennation angle of 41 degrees. They compared this to a parallel muscle containing ten fibres of 20 cm each.

The pennate muscle generates approximately twice as much force as the parallel muscle (figure 2.8), with a non-linear displacement of approximately 5.5 cm as compared to 6.8 cm for the parallel muscle. This type of stiffness decreases non-linearly with muscle contraction, which might be useful in designing exosuits for resistance training, where large forces are required.

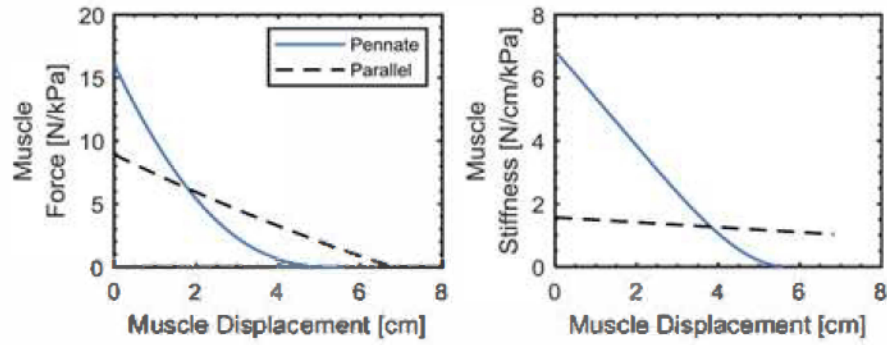


Figure 2.8: Force and Stiffness comparison between Pennate and Parallel Muscles. Modelled by Jenkins et al. (2019)

Chapter 3

Research Methodology and Design Process

3.1 Design Process

Developing a solution to a complex problem with novel methods requires careful assessment and comprehensive research. Considerations include the intended purpose, the environment, and the device's capabilities. This study employs a design process that includes multiple stages to effectively brainstorm an effective solution to developing a lower-limb exosuit for human rehabilitation and space application (figure 3.1). The design process facilitates increasing confidence in the solution, mitigating risks and problems, ensuring safety, reducing costs, and making it practical for its intended use (M. C. Yang 2005).

In the design process, a set of problem statements and primary goals are first defined. Developing robots to assist astronauts in space requires thoroughly considering the environment, limitations, and constraints. The ISS, for example, has limited operating space and resources (Douglas, Wheeler, and Fritsche 2021). It is essential to define the problem statement to clarify its objective and ensure that the solution suits the intended user and the environment. Following the identification of the problem statements, the next step involves researching tested and existing solutions.

Considering that this research aims to develop exosuits for astronauts, the design must conform to the natural structure of the human body (NASA 1995). Therefore, a fundamental part of this research involves a thorough understanding of biomechanics and human physiology. The latest advances are identified as part of the research phase, and previous failed designs are avoided. This stage involves reviewing the background literature, conducting primary research, consulting with users and experts, and understanding the user's needs in greater detail. As a result, the information gathered will be used to develop and design the exosuit, ensuring that it incorporates the latest and relevant technologies, as it could also be used for human rehabilitation on Earth. Further, this stage contributes to identifying any potential risks or challenges associated with the development of the exosuit, allowing those risks and challenges to be addressed early in the design process.

Following the completion of research and information gathering, the next phase involves designing the exosuit. During this phase, ideas and concepts are brainstormed, and detailed design specifications are developed for the physical structure, sensors, and actuators of the exosuit. Various mechanical, electronic, and material solutions are explored during the concept generation phase for the lower limb exosuit. Multiple conceptual designs can be generated in this phase. Different concepts regarding feasibility and functionality can be assessed using computational modelling, simulations, and prototypes. A number of factors are considered when determining how to optimise performance and user experience, including actuation mechanisms, joint configuration, control systems, and attachment methods.

Design processes should consider the robot's intended use, as well as any constraints or limitations uncovered during the problem definition process. In addition, the design process should also consider factors such as cost, ease of use, scalability, power requirements, and effectiveness to ensure that the exosuit is practical for its intended use. After the initial design has been developed, the next step involves developing a prototype or simulating it for validation and verification.

The validation and verification phase is where the design is eventually turned into a physical prototype by an iterative process, which can be tested in a controlled environment (Anderson,



Figure 3.1: The Design Process.

Ellis, and Weiss 2007). This stage is essential in identifying potential issues or designs flaws before deploying the exosuit in the intended environment. A rigorous testing process is necessary to ensure the product meets its intended functions and meets the design specifications. Any design flaws that are identified during testing should be addressed during the revision process. As part of the safety evaluation process, the exosuit must be tested in real-world scenarios for performance, reliability, and safety to ensure that it meets relevant safety standards and regulations. As a result of the robot's deployment, it is vital to consider its ethical implications, such as its impact on workers and society. The safety and effectiveness of the exosuit solution should be ensured before it is deployed, and any issues or concerns identified during testing and

evaluation should be addressed.

To conclude, developing robotic solutions is a complex and multi-stage process that requires meticulous planning, research, and evaluation. In order to ensure a robot is safe, effective, and practical for its intended use, each stage of the process must be followed carefully. It is possible to create robots that can solve various problems and improve efficiency and productivity in various industries by defining the problem, conducting research, generating ideas, prototyping, testing, evaluating, refining, producing, and deploying. Nevertheless, it is vital to remember that the development of robots also raises ethical questions and concerns. It is vital to remember these concerns throughout the design process so that robots are deployed responsibly.

3.1.1 Design Considerations

In developing the design criterion, the specification and requirements below are the considerations taken to devise an optimal design systematically. Here are some design considerations that should be taken into account:

3.1.1.1 Knowledge of natural human kinematics, kinetics and user circumstances

Knowledge of natural human kinematics, and kinetics enable designing the soft exosuit to conform to the human natural shape and biomechanics. This consideration allows the exosuit to be bio-inspired and minimise interference to natural gait, locomotion or movement (Missiroli et al. 2020; Basla et al. 2022).

3.1.1.2 Compliance and Kinematics matching between exo-suit and the wearer

The human anthropometry including shape, size and composition varies in human. Consequently, the soft exosuit must be customised according to the intended user to enable optimal kinematic alignment between the wearer and the exosuit (Xiloyannis et al. 2019). Since the exosuit does not have its own structural frame, the transfer of reaction forces relies on the structural characteristics of the human body. This highlights the importance of compliance between the exosuit and wearer, and self alignment of kinematics must be ensured to enable seamless transfer of forces.

3.1.1.3 Weight, size and mobility of the exosuit

Weight becomes a concern for humans performing rehabilitation on Earth or astronauts returning to Earth from their space mission when re-exposed to Earth's gravity. Therefore, it is a requirement that the weight of the exosuit is lightweight in all intended environments (Morris et al. 2023; Calanca et al. 2020). The operational space in which the astronauts perform tasks is also limited. As a result, the exosuit needs to be flexible, lightweight and compact. Since the exosuit is intended to be worn throughout the space mission, it must not restrict natural human movements and should allow smooth mobility.

3.1.1.4 Sensing and Control Strategy

Sensing and control strategies for exosuits in both space and rehabilitation contexts requires careful consideration of several key factors. In space, the exosuit must be capable of sensing and responding to changes in the environment, which includes but not limited to changes in pressure, temperature, or radiation to ensure the safety of the astronaut. The sensing and control strategy must also be able to sense key performance indices to monitor effectiveness of the exosuit and achieving desired results (Tiboni et al. 2022).

For rehabilitation on Earth, the sensing and control strategies must provide assistance and support for the wearer while accommodating individual differences in anthropometry and movement patterns (Garrec 2010). The exosuit must be designed to provide adequate sensing and control for specific tasks, while be easy to use and promote recovery (Tiboni et al. 2022).

Overall, designing effective sensing and control strategies for exosuits requires a deep understanding of the intended application and user requirements to achieve optimal performance.

3.1.1.5 Power and Actuation Requirements

The power and actuation requirements of the exosuit should be energy efficient, which not only allows repeated use of the technology but also reduces energy costs (Tiboni et al. 2022). In both contexts, space and for human rehabilitation on Earth, the exosuit should be powered with minimal power requirements given the limited resources on the ISS and associated costs

on Earth. Hence, the exosuit should be lightweight and utilise actuators demanding minimum power (Calanca et al. 2020).

3.1.1.6 Human-Robot Interaction and Ergonomics

Human-robot interaction along with ergonomics are essential design considerations for the exosuit in both contexts - the space and human rehabilitation. The human-robot interaction includes considerations such as ease of use, feedforward and feedback mechanisms. This can include user feedback through auditory, visual or haptic, as well as being able to deduce anticipated movements. Therefore, the use of the exosuit must employ intuitive controls that minimise cognitive workload and user inputs (Tacca et al. 2022).

In space application, the user must be able to interact with the exosuit without any concerns as troubleshooting in space is limited with the ground support. Furthermore, the astronauts must be able to perform tasks without putting any other member of staff or equipment at risk. The same principle applies for human rehabilitation, where the user must not endure fatigue or injury during the use of the exosuit (Xiloyannis et al. 2019). A balance between user and technology needs is critical in the designing the exosuit, where ergonomic study can provide a reasonable input to maintain this balance and ensure user satisfaction without degrading performance.

There are several factors concerning ergonomics in conjunction with the choice of garment materials, including but not limited to comfort, absorbency, breathability, and stretchability (Zhu et al. 2023). These factors affect the regulation of body temperature and, in turn, will affect the long-term wear of the exosuit (S. J. Park et al. 2022).

3.1.1.7 Re-usability, Maintenance and Fatigue Properties

The space environment is hostile, where humans may encounter high radiation and other hazards. Hence, the exosuit design must perform in extreme temperatures, radiation, and other hazards encountered in space (S. J. Park et al. 2022). The exosuit should also be durable to withstand prolonged use in space and on Earth (Rupal et al. 2017). The exosuit should be designed to allow for easy maintenance and repair.

3.1.1.8. Cost Effectiveness and Efficacy

Cost-effectiveness and efficacy are critical considerations when designing exosuits for use in space or human rehabilitation on Earth. The high costs of space missions highlight the importance of cost-effectiveness, while efficacy ensures the astronaut's safety. Thus, the exosuit must be designed to provide maximum functionality while minimising costs (Nguyen and W. Zhang 2020).

In rehabilitation settings, the exosuit must be cost-effective to increase accessibility, while efficacy is necessary to provide practical rehabilitation support. The cost of the device has been cited as a significant impediment to its use by both physiotherapists and the end-user (Vaughan-Graham et al. 2020). Therefore, exosuit design must consider materials, manufacturing processes, and usability to ensure maximum benefits for the user at a reasonable cost.

By considering these design considerations, exosuits for astronauts can be designed to provide adequate protection, mobility, and functionality required for astronauts to perform their tasks in space.

3.2 Proposed Actuation Simulation and Experimental Fabrication

The design of the exosuit depends upon the actuation method chosen. The TCAs have proven promising, as reviewed in section 2.4. The TCA fabrication methods are discussed in figure 3.2. A rotary machine is attached to one end of the fibre, for example, a drill or bench drill, while the other is fixed to a specific weight (distal end). Once the rotary machine is turned on, the fibre is twisted, and once a critical turn limit is reached, the fibre will spontaneously form coils. The fibre shortens longitudinally as it shortens, which also causes its weight to increase. In order to remove internal stresses, the fibre is annealed in an oven at a specified temperature after twisting and coiling (Carter S. Haines et al. 2014).

The weight influences two critical parameters during fabrication at the distal end of the nylon

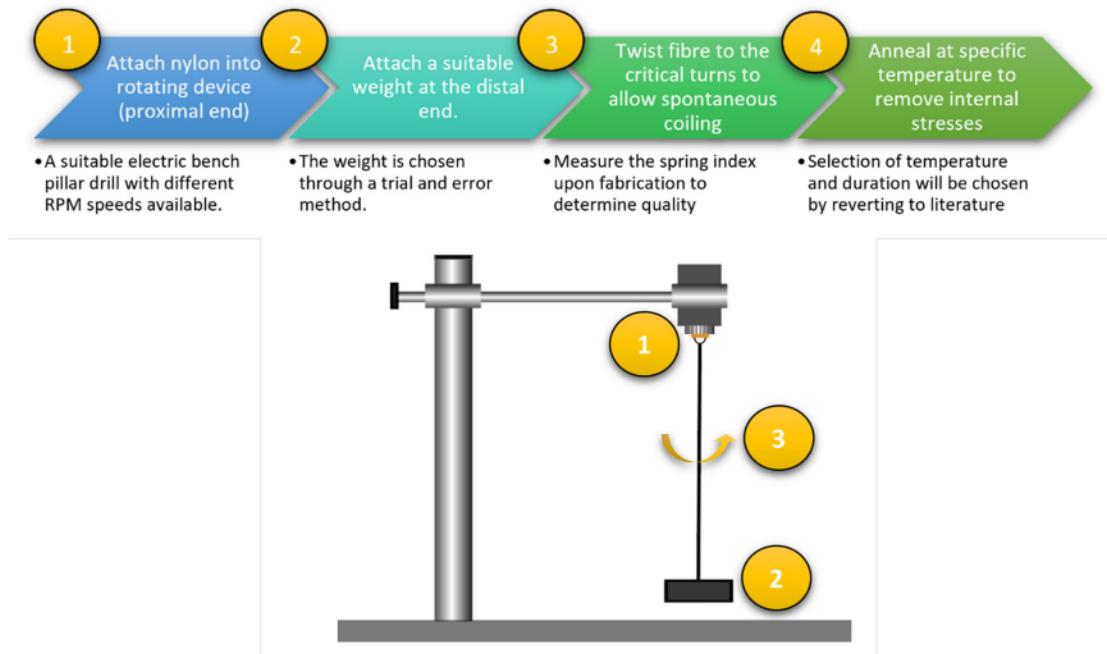


Figure 3.2: The fabrication process of the TCA.

fiber: the critical turn index and the spring index. Considerations are provided in Table 3.1. The larger the weight, the smaller the spring index. The larger the fibre diameter, the higher the spring index. For instance, a fibre diameter of 0.5mm and 0.4mm at 250 grams produced a spring index of 3.45 and 2.82, respectively (Yin et al. 2018). For reasons outlined below 3.1, the spring index should not be less than 3. It has been observed that nylon fibres with larger weights produce lower critical turns. However, low weights introduce flaws (Yin et al. 2018). Larger-diameter fibres produce coiled fibres with a lower critical turn.

After annealing, the fibre retracts to a certain extent. The temperature at which the fibre anneals influences this percentage. For example, the higher the temperature at which the fibre is annealed, the smaller the percentage of fibre retracting. This study intends to initially incorporate silver paint as a conductive source as materials are readily available, and fabrication is straightforward, as described by Mirvakili et al. (2014).

3.2.1 Bioinspired Actuator and Proposed Simulation Study

Once multiple fibres have been fabricated and tested for their force output, resistance, and spring properties, a parallel arrangement of the same volume will be compared with a pennate

Table 3.1: Parameters associated with the TCA fabrication with its considerations.

Parameters	Consideration
Fibre Diameter	The diameter influences all parameters stated below and, the larger the diameter, the more energy to heat is required
Spring Index	This is the ratio between the coil diameter of the TCA and the fibre diameter. The lesser the index, the higher the sharpness of curvature. Spring index less than 3 indicates the stresses in the wire excessive and can cause material fractures and cracks.
Critical Turns	An essential number of turns to enable spontaneous coiling. There should be an optimal weight window. Such that, the larger the weight, the more critical turns required, however, the fibre could break if the weight is excessive. If the weight is too low, flaws could be introduced.
Annealing Temperature	To eliminate internal stresses and loosen the TCA. The temperature influences the retraction of the nylon upon removal from clamps after the annealing process

arrangement. The illustration in figure 3.3 is for experimentation purposes only. The fibres would be attached to the frame using eye pins. The fibres would be oblique to the large fibre in the original form of pennate architecture at 45 degrees. Moreover, the large fibres would be made of nylon fishing lines that are passive and unactuated. A metal paperclip would hold the load at the end of the large fibre. The parallel architecture would not require a large fibre since the fibres would carry the load.

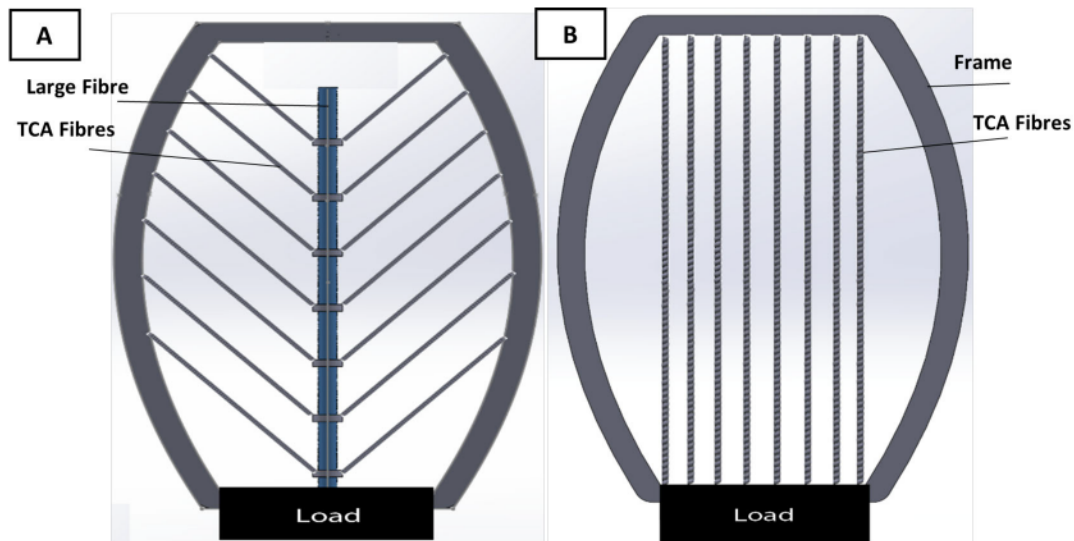


Figure 3.3: Testing method to compare parallel and pennate architecture muscles **A)** Pennate architecture frame **B)** Parallel architecture frame. Image Source: Author

As the AGR is the ratio between the input force of the small fibers and overall output force, the AGR is given in Equation 3.1:

$$\text{AGR} = \frac{F_{\text{out}}}{nF_{\text{fibres}}} \quad (1) \quad (3.1)$$

where F_{out} is the muscle force generated, F_{fibres} is the force of each fiber, and n is the number of fibers. The F_{out} could be calculated by Equation 3.2:

$$F_{\text{out}} = nF_{\text{fibres}} \cos(\theta) \quad (2) \quad (3.2)$$

where θ is the pennation angle. In the experimentation, the force would be measured using a force sensor. A comparison between each design would influence the design of the actuator unit subsequently. The original design would be compact and cover as much surface area as possible with the consideration of heating-cooling cycle times.

3.2.2 Kinematic and Muscle Activity Proposed Study

A study of the kinematics and muscle activity will be proposed utilising a motion capture system and sEMGs, respectively, to achieve a complete understanding of muscle function, joint torque requirements, and muscle motion during various resistive exercises in order to grasp the differences between them fully.

This study seeks to investigate how different weight intensities and exercises without weight affect kinematics, muscle strength, volume, and endurance in healthy individuals. The proposed study could be a randomised controlled trial conducted on the impact of different weightless exercises on kinematics.

Inclusion criteria include healthy people between 25 and 45, with an average *body mass index* (BMI) of 18.5-24.9, and who exercise mildly to moderately. A range of age and BMI was selected to reflect NASA's selection requirements for astronauts (Dean 2018). People with long-term co-morbidities, including strokes or major surgeries, as well as those who have participated in

high-intensity training, would not be eligible to avoid bias. Before participating in the study, a questionnaire designed with the assistance of relevant experts such as physiotherapists will be required to assess their fitness level and acceptability.

In consideration of the time constraint and to enhance the statistical power, a minimum of 60 participants should be divided equally between three groups of equal size. Weight groups include 'no weights', 'light weights', who can exercise with weights ranging from 30 to 50 percent of the participant's *maximum one repetition* (1RM) or 'heavy weights', where they can exercise between 75 and 90 percent of their 1RM, following a range commonly studied in resistance training research (Fernandes et al. 2022). Resistance exercises may include squats, pull-ups, push-ups, or resistance bands. A minimum of 8 weeks will be required for the study, where participants exercise twice a week, doing the same sets and averaging the same amount of exercise time, mimicking the exercise protocol of (Aube et al. 2022).

This study aims to evaluate the effects of weight conditions on exercise performance and muscle adaptation by employing several outcome measures. Valuable insight can be provided into how weight conditions impact movement mechanics during exercise by analysing joint angles, range of motion, and movement velocity. The results of this analysis could provide a deeper understanding of the kinematic characteristics of the subjects throughout the program.

As part of the evaluation of muscle strength, 1RM testing on standard exercises like the bench press, squat, and deadlift can determine whether strength has changed over the course of the program. A repetition maximum test could be conducted under each weight condition to assess muscular endurance and the subject's ability to sustain exercise efforts under each weight condition.

As an added assessment method, it is possible to use ultrasound imaging to measure changes in muscle thickness following the exercise program to assess the effects of weight conditions on muscle adaptations. This non-invasive method will make it possible to identify any hypertrophy that has arisen from the exercise program.

Statistical methods such as *analysis of variance* (ANOVA) can be used to analyse data gathered

from these outcome measures. By doing so, a comparison of the means of the three independent groups for each outcome measure can be conducted. Post-hoc pairwise comparisons will also be conducted to examine any significant differences between the three groups. Tests should be conducted with $p = 0.05$ level of significance, and analyses should be conducted with SPSS Statistics v29 (IBM Corp., 2023).

It is imperative to acknowledge potential limitations. Non-adherence to the exercise program, individual differences in exercise form, nutritional intake, and sleep patterns could potentially influence the outcome. In order to ensure the validity and accuracy of our findings, tracking and accounting for these variables is crucial during data analysis.

Astronauts exercise using resistance devices. This research will help scientists develop better resistance devices for astronauts. Using kinematic analysis to compare exercise with and without weights can help researchers design better resistance devices for space exercise. Additionally, determining which type of exercise provides the most significant impact on muscle strength and endurance can aid astronauts in determining the intensity of resistance training they should perform to maintain their musculoskeletal health.

To combat muscle atrophy, a significant issue in spaceflight, researchers can determine the effectiveness of various resistance training intensities by measuring muscle thickness. In addition, kinematic assessments provide valuable insight into how body movement and joint angles vary due to weight use. Due to the unique way, the body moves in microgravity, it may be possible to formulate more effective exercise protocols based on this information.

Astronauts could benefit from the findings by designing effective pre-flight and post-flight exercise programs that will assist them in preparing for space travel and recovering after returning from space. By enhancing astronaut health and performance during long-duration space missions, this study can provide valuable information to enhance current knowledge and inform future recommendations regarding exercise protocols for space-based missions.

Chapter 4

Design Proposal

4.1 Soft Exosuit Design - Initial Concept

During the second phase of the design phase of our project after defining the problem statements, end user involvement was crucial to ensuring the design met real-world expectations and needs. A detailed background literature review and discussions with a diverse group of potential users, field researchers, physiologists and end-users were conducted to determine their practical requirements and preferences. In this study, at least seven end-users undergoing resistive exercise as part of their conventional rehabilitation were engaged in casual discussion. To develop use case scenarios as well as potential solutions and hypotheses, human physiology, existing solutions and socio-economic factors were assessed. For given case use scenarios for astronauts, it was not possible to reach astronauts directly for their opinion on potential use of exosuit use because they were not available, but publicly available resources and interviews provided some understanding of their needs in space (Space Safety Magazine 2012; Plessis, Djouani, and Oosthuizen 2021; Pulvirenti et al. 2022; The Franklin Institute 2018).

Insights gained from field researchers and end-users influenced the design. In the study, users stressed the importance of simplicity in design, emphasising that it should be user-friendly and easy to operate, even for people with no technical background. As a result, the ease of use of a product is often a key determinant of its success, in line with the trend of user-centred design.

In addition, users expressed a strong preference for a product that is discreet and aesthetic. They preferred a design that could be easily incorporated into their day-to-day lives and not draw attention to itself. In order to ensure user confidence and comfort, as well as to encourage regular use, this design aspect was particularly important.

Another crucial factor highlighted by end users was comfort and cost. Patients and elderly users, for whom physical comfort is paramount, emphasised the importance of the product feeling good on their bodies, without causing any discomfort or physical strain during use. Wearable technologies and soft exosuits demonstrate that ergonomically sound designs align with human bio-mechanics, as discussed by physiologists and field-related researchers in this study.

The human body's muscle routing was the inspiration for the design of the exosuit, as determined by the detailed literature review, secondary research, and primary research. The Initial concept of the design is given in figure 4.1. However, it is pertinent to mention that the design is subject to revisions as the research progress. For ease of viewing, the exosuit is only shown for one leg. The current design focuses on the quadriceps and hamstrings, and upon successful implementation, the same concept could be extended to the tibialis anterior and the triceps surae. Phases for the design given in table 4.1.

Table 4.1: Phases of Lower Limb Exosuit Training

Phases	Muscle Group Focus	Requirement
Phase 1	Quadriceps and Hamstrings	Exercise
Phase 2	Triceps Surae and Tibialis	Exercise
Phase 3	All Leg Muscles	Assistive

The exosuit contains a butterfly-shaped waist-belt for anchoring the *proximal thigh webbings* (PTW). The anchor points in the waist-belt are located at the region where the iliac spine would be located in a human being. There are three upper leg muscles, namely the *Vastus Lateralis* VL, *Vastus Intermedius* VI, and *Rectus Femoris* RF, which are represented by the three upper leg webbings. With the help of actuator units, the PTW is connected to the *distal thigh webbings* (DTW). The anchor points for the VI and VL webbing are at the proximal calves' strap, while the RF webbing extends to the distal calves' strap. As these muscles insert

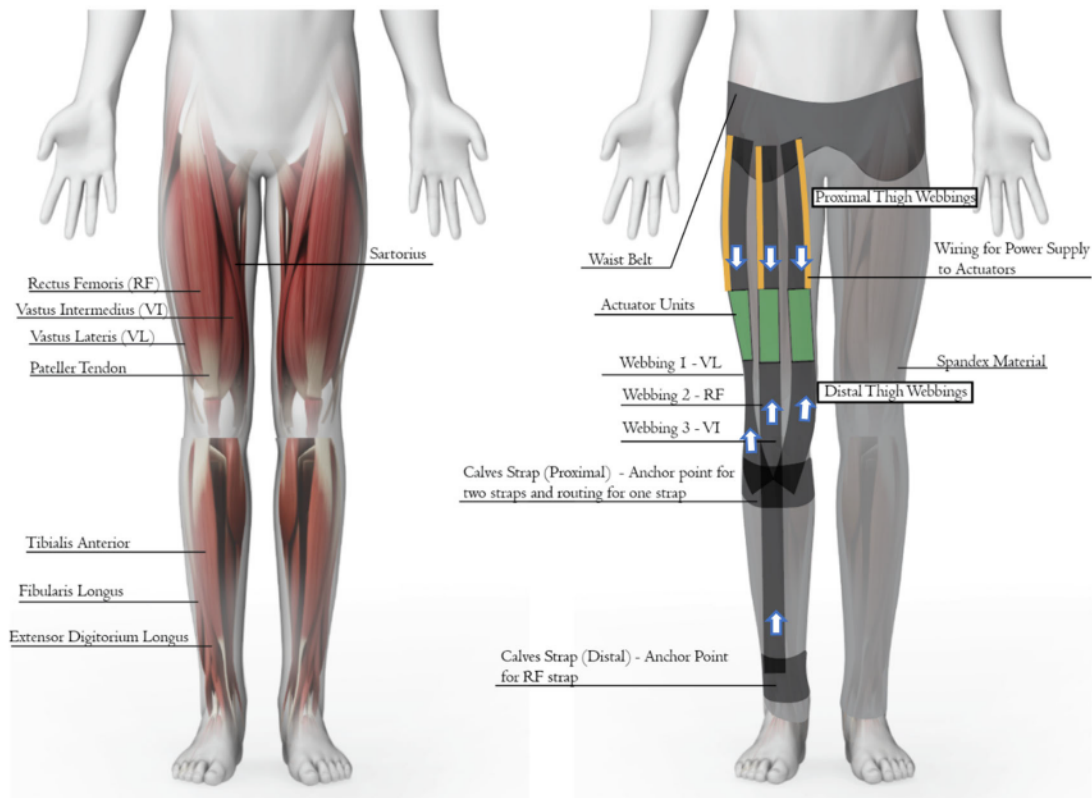


Figure 4.1: Proposed novel design of the soft exosuit. Image Source: Author

into the human body through the tibial tuberosity, the proximal calves strap is chosen as a mimic. The RF webbing, however, extends to the distal calves' strap to increase the lever arm, so the proximal calves strap also serves as an insert for the RF webbing. VI and VL webbings do not extend for two primary reasons. First, misalignment could result in shank rotation, and second, the region should be left bare for the webbing of the tibialis.

Actuators will generate forces illustrated by blue arrows in figure 4.1, and subsequently, the DTW and PTW become closer, resulting in a contraction. This action results in knee extension. To perform the hamstring exercise through hamstring curls, the user would need to resist the actuation of the exosuit by flexing their knee, and therefore, they would need to engage their hamstrings by concentric contraction. As the actuation stops, the webbings release their stored energy, resulting in knee flexion. Therefore, the user would need to extend their knee to allow eccentric contraction slowly.

Forces within the exosuit should be evenly distributed to avoid high-pressure points that could

lead to discomfort regions. Shear forces are unavoidable through the webbings and could cause discomfort if higher than 0.5 N/cm² (Quinlivan et al. 2017). Both calve' straps and the waist belt are joined through a spandex layer, a highly elasticated and thin material. The webbings are above this layer, reducing the shear stresses dissipated through the inner layer and providing more comfort to the user. Precise routing of the webbings would be chosen upon a thorough joint reaction forces analysis to determine forces on the joints.

These aspects are addressed by tailoring the trousers to the particular subject matter. To ensure an adequate elastic response in response to force applications, polyester webbing will be used for stretchable parts. A lateral zip can be sewn to facilitate quick donning and doffing procedures.

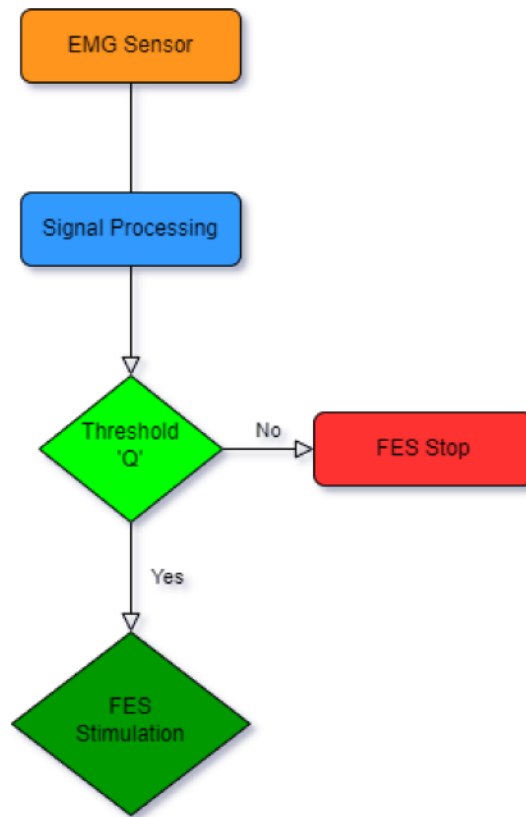


Figure 4.2: FES-EMG Control.

The FES electrodes shall be incorporated with EMG sensors that monitors the muscle activity of the target muscles. By monitoring the electrical activity of the muscles under the skin, the EMG sensors provide real-time biofeedback to the system. This system has many advantages,

including increased muscle strength and volume maintenance, increased functional mobility, and the option of personalised therapy since it can be adapted to meet the individual's unique needs. Having weakened muscles due to conditions like paralysis, atrophy, or prolonged microgravity could make it particularly useful for individuals with weakened muscles. Using the electrodes, the controller would then deliver electrical signals to the muscles, causing them to contract (figure 4.2). There are four regions in which the FES is placed on the exosuit - the gluteal area, the thigh area, the calf area and the foot area. The gluteal area includes the gluteus maximum, medius and minimum. The quadriceps and hamstrings make up the thigh. In the calf, there are the gastrocnemius and soleus, which are anti-gravity muscles. In the foot, there is the tibialis anterior, which is involved in dorsiflexion.

4.2 Considerations for the Actuator Design

The shape architecture of lower limb muscles varies from muscle to muscle, and this, in itself, illustrates the muscle's functional importance. In Table 4.2, we describe the essential muscles with regard to fiber arrangement, PCSA, peak force, optimal length, and pennation angle (Arnold et al. 2010).

Interestingly, the VL produces a higher force than the other three quadriceps muscles. However, the *Vastus Medialis* (VM) and RF are parallel to each other, and therefore, produces a combined force similar to that of VL. The soleus is the only muscle that is multi-pennate and produces a more significant force compared to the other muscles, which indicates its importance in its function. It is apparent from table 3 that PCSA is the essential factor in producing higher forces, and the fibre arrangement and pennation angle significantly influence the PCSA. The actuators would be designed, tested, and compared according to these factors.

Conventional resistance training methods further typically vary task intensity through progressive schemes, such as increasing the band stiffness or adding higher weights to the foot over time (Wu and Chen 2012; Asbeck et al. 2014). In contrast, most existing literature investigating joint and stance specific resistance with wearable devices do not systematically vary the applied resistance force magnitude (Liu and Nancy K Latham 2009; Karlsson et al. 2013;

Table 4.2: Muscle properties and fibre arrangements for the lower limb muscles.

Muscle	Fibre Arrangement	PCSA (cm ²)	Peak Force (N)	Optimal Length (cm)	Tendon Slack (cm)	Pennation Angle
Quadriceps						
Rectus Femoris	Bipennate	13.9	848	7.6	34.6	13.9
Vastus Lateralis	Bipennate	37.0	2255	9.9	13.0	18.4
Vastus Medialis	Bipennate	23.7	1443	9.7	11.2	29.6
Vastus Intermedius	Bipennate	16.8	1024	9.9	10.6	4.5
Hamstrings						
Semitendinosus	Fusiform (Parallel)	4.9	301	19.3	37.8	19.3
Semimembranosus	Unipennate	19.1	1162	6.9	24.5	6.9
Biceps Femoris (lo)	Fusiform (Parallel)	11.6	705	9.8	32.2	9.8
Biceps Femoris (sh)	Fusiform (Parallel)	5.2	315	11.0	10.4	11.0
Triceps Surae						
Gastroc. Medial	Bipennate	21.4	1308	5.1	40.1	5.1
Gastroc. Lateral	Bipennate	9.9	606	5.9	38.2	38.2
Soleus	Multipennate	58.8	3585	4.4	28.2	28.2
Tibialis						
Tibialis Anterior	Circum-pennate	11.0	673	6.8	9.6	9.6
Tibialis Posterior	Circum-pennate	14.8	905	3.8	13.7	13.7

Note: Values for the PCSA, Peak Force, Optimal Length, Tendon Slack, and Pennation angle are given by a computational model in Opensim. The model was produced through experiments on 21 cadavers, conducted by (Arnold et al. 2010)

Powers et al. 2016; Scherbakov et al. 2013; Narici and Maffulli 2010; Fernandez-Gonzalo et al. 2016), and thus there is little knowledge of how resistance magnitude should be set to modulate intensity at the ankle. People post-stroke and healthy individuals often rely on proximal joints or the contralateral limb to compensate for ankle weakness (Lund et al. 2018) or for high intensity tasks such as incline walking (Orr 2010; Dorsch, Ada, and Alloggia 2018). Consequently, joint-specific resistive forces that are too high may result in over-reliance on the unresisted joints, which negates the intent of targeting a specific joint. Hence, it is critical to identify the resistance level that results in minimal changes at the unresisted joints while increasing plantarflexor effort at the resisted ankle joint.

Furthermore, it was observed that at the highest applied resistance magnitudes, individuals increased reliance on the unresisted contralateral limb and ipsilateral proximal joints (Lund et al. 2018; Dorsch, Ada, and Alloggia 2018). These trade-offs were negligible at lower forces, suggesting that with an appropriate force level, the resisted joint can be targeted more exclusively. The study also demonstrated that peak plantarflexor angle increased relative to baseline upon removal of resistance, but only at an intermediate force magnitude. This exosuit could potentially be used for training increased plantarflexor effort during mid-late stance for individuals post-stroke.

Chapter 5

Summary and Future Outlook

5.1 Discussion

Developing a lower limb exosuit for astronauts poses several challenges. These challenges include aspects of biology, material science, robotics, human factors, ergonomics, and engineering obstacles. Solutions tailored to the unique requirements of operating in a space environment requires an interdisciplinary approach.

Astronauts undergo a complex physiological adaptation due to microgravity, which can have short-term concerns as well as long term implications. A person's ability to perform tasks could be severely compromised by these adverse effects, especially in missions involving the exploration of other celestial bodies' surfaces. Therefore, one of the first considerations in designing such an exosuit is biomechanical and physiological factors. It is essential that an exosuit designed for such applications not only offer mobility but also simulate the biomechanical pressures experienced on earth to counterweight the effects of weightlessness with the necessary stimuli. This is a limitation that researchers are attempting to mitigate so that longer duration and further space missions can be a reality.

Currently, the countermeasures in space require the astronauts exercising in specially built exercise devices, such as the ARED in the ISS. However, the current exercise protocols are unable to fully mitigate the adverse physiological effects, and it is uncertain how the human

body will adapt in deeper missions where stressors are more severe. Furthermore, these exercise routines are time-consuming and the problem still persists. The case of exoskeleton use, or specifically, exosuits, is an attractive alternative that can maintain the musculoskeletal integrity of the astronauts.

Through the design of this exosuit, continuous physical training can be provided while performing everyday activities. This is without the need to dedicate time and space to physical training. Since continuous low-intensity resistance training provides similar results as high-intensity training. By introducing such wearable devices, all astronauts will experience an innovative paradigm for physical training. It has been proposed that a functional exosuit with a comprehensive array of sensors, actuators, and soft structures can be developed that incorporates exercise requirements and long-term user comfort into the concept. In the first phase, this will allow continuous all-day training of the lower limbs, and in subsequent phases, it can be extended to include the upper limbs and other body parts. By doing so, astronauts can train their limbs as they would under normal gravity on Earth without spending much time maintaining their health.

An integral part of maintaining muscle strength and volume could be by integrating FES-EMG in the exosuit. By delivering controlled electrical pulses to muscles, FES mimics the natural process of muscle contraction. EMG, on the other hand, measures the electrical activity produced by the skeletal muscles in real-time, enabling real-time assessment of muscle condition and the effectiveness of stimulation. It is possible to establish a closed-loop control system by integrating an FES system with an EMG system within the exosuit. Muscle engagement can be optimised through personalised and adaptive stimulation patterns, thus maintaining muscle strength and volume even without regular weight-bearing exercises. By combining these approaches, astronaut musculoskeletal health could be effectively counteracted.

Exoskeletons and exosuits currently in research are generally intended to restore or supplement lower-limb strength and have demonstrated promise to assist individuals with musculoskeletal injuries and disorders. Nevertheless, their use may extend beyond simply restoring or augmenting motor function. The impact of lower limb exosuits on cardiovascular and neurological

health is of growing interest. The purpose of this discussion is to highlight the potential health benefits of these innovative devices in promoting low to moderate lower-limb exercises.

Research has demonstrated that regular resistive and endurance physical exercise reduces risk factors associated with cardiovascular diseases, such as hypertension, hyperlipidemia, and insulin resistance. Lower limb exosuits can assist individuals who cannot perform these exercises independently due to weakness, injury, or disability. By offering customisable levels of support, it can provide a safe means of engaging in regular physical activity and potentially improve cardiovascular health. Furthermore, this exosuit can be used to help patients with OI engage in upright exercises, thereby improving autonomic regulation and gradually adjusting the body to positional changes. An exo-suit, for example, has been developed by researchers to aid in transitioning from sitting to standing without experiencing dizziness or fatigue associated with orthostatic intolerance. This becomes more vital in future missions of astronauts to the moon or the Mars given the absence of medical assistance.

Additionally, exosuits can help to maintain neurological health of the astronauts by increasing neuroplasticity, improving cognitive function, and spatial orientation. Using this exosuit may enhance the user's awareness and proprioception of the body in space and reinforce neural pathways associated with spatial cognition by providing subtle cues about limb position and movement. Furthermore, due to the adjustable intensity of support provided by this exosuit, exercises can be tailored according to the individual's abilities and progress, promoting a gradual neurological adaptation.

On Earth, neurological conditions such as stroke and Parkinson's disease can cause mobility impairment in patients. These patients can benefit from exo-suits by participating in lower limb exercises, which are crucial to physical rehabilitation and brain health. Several adverse effects of neurological conditions can be mitigated by exercising, which releases neurotrophic factors which promote neuronal health and growth.

Many advantages are offered by this exosuit design. However, there are also several challenges associated with it. A critical element of robotic integration is the balance between the enhancements provided by robotics and the astronaut's need for natural movement and proprioception.

Control systems for robotic integration will also need to be carefully designed. To maintain the safety and performance of astronauts, it must be capable of providing smooth and intuitive operation without introducing latency or cumbersome controls that could compromise their performance.

The user comfort and ease of use are also essential, posing significant design constraints. Providing comfort for a wide range of body shapes and sizes requires a highly adjustable or customisable design. The exosuit could become more complex and heavy, increasing engineering and logistics challenges. In addition, extended wear could result in heat dissipation problems and skin irritation if the exosuit is worn for an extended period. In light of these factors, the duration of wearing the exosuit may be limited, counteracting the positive effects of continuous muscular stimulation or locomotive assistance. The design process must incorporate these potential problems and develop practical solutions or compromises.

A thorough kinematic study is necessary to understand the design criteria for the lower limb exosuit. In order to determine the range of motion, speed, and acceleration that the exosuit should be capable of supporting, kinematics is studied without considering the forces causing it. As a result, an exosuit can be designed that is biomechanically compatible with the user, allowing it to support natural and efficient movement. By conducting a kinematic study, the exosuit's design can be tailored to accommodate each astronaut's unique movement pattern and physiological characteristics.

A comprehensive kinematic study as part of the current project could not be conducted because of time constraints and external factors beyond our control. This limitation should be acknowledged in this research. In the absence of this kinematic information, the design of the exosuit may be limited in its specificity and effectiveness, which could result in decreased performance or comfort for the astronaut. Therefore, future research efforts should be focused on conducting a thorough kinematic study to refine further and enhance the design parameters of the exosuit.

In space, it is possible to address some of the challenges associated with exercising by using new, innovative actuators in exercise equipment. Traditional exercise equipment is large and heavy and requires significant space to operate. This is not ideal for the confined environment

of a spacecraft where space is limited, and especially where new spacecrafts are designed to be much smaller than the ISS. Additionally, the power generation is insufficient to provide the same ground reaction forces as on Earth.

The parallel actuator design replicates muscle architecture in the human body, where the fibres are parallel to the direction of action, allowing for a faster contraction and a greater range of motion. However, the parallel actuator has limitations, such as its limited ability to generate force. Alternatively, a pennate actuator could be designed to be more compact and lightweight. Most importantly, the pennate arrangement allows for more muscle fibres to be packed into a smaller volume, which may result in more significant force generation. High intensity force-generating muscles possess such an architecture, such as the soleus.

The ability to fully understand the potential applications and limitations of parallel and pennate actuators in the context of space exercise equipment requires a comprehensive comparison. Despite the advantages of both actuators for space applications, their suitability will primarily be determined by the specific requirements of the exercise equipment and the astronaut's physiological requirements. Parallel actuators could be more effective in fast movements, however, it may not be able to maintain muscle mass and bone density. Conversely, pennate actuators may be more effective for exercises involving high resistance due to their higher force generation. The compact size of these devices might also be a significant advantage in the restricted space of a spacecraft.

Consequently, the choice between parallel and pennate actuators should be based on careful consideration of these factors, as well as other factors such as the reliability, stability and ease of use of the actuators. Additional research will be necessary, including experiments and prototype testing to make an informed decision.

Space travel in the future is due to increase, especially to Mars and other planets. Longer exploration and missions will invite challenges to the musculoskeletal, cardiovascular and neurological health. Furthermore, research has found that bone remodelling and atrophy occurs even after six months of space-ship. Long-term cancer risks could also occur as a result of radiation exposure. Therefore, it is essential to discover and invent new technologies, such as

exosuits, that can prevent physiological adaptations, since space crew members will be more distant, secluded, and independent from Earth making timely medical assistance difficult.

Aside from space missions, exosuit technology is increasingly used for rehabilitative purposes on Earth, such as helping patients recover motor function following a stroke or SCI. Tailored rehabilitation programs can be provided with adjustable support levels, which promote patient engagement and recovery. Exosuits can improve training efficiency and safety, reducing the risk of injury and maximising performance in various disciplines. Using exosuits in the workplace, particularly in physically demanding jobs, may assist in preventing musculoskeletal injuries and fatigue. Furthermore, exosuits can enhance independence and improve the quality of life for individuals with mobility impairments or age-related weakness decline.

A new frontier in healthcare, sports, workforce safety, and space exploration will likely emerge as technology advances, with the potential applications of exosuits likely to grow. Exosuits have the potential to revolutionise the way we work and interact with our environment, making heavy lifting and long-term physical exertion safer and more efficient. As technology continues to evolve, it could be used to improve accessibility and inclusion for those with physical disabilities. Ultimately, exo-suits could be an invaluable tool in the workplace, providing a safe and effective way to increase productivity.

5.1.1 Exosuit Applications in Space and on Earth

Space astronauts may be able to maintain muscle mass and bone density by wearing exosuits designed to provide resistance as exercise equipment. As a result of the use of exoskeletons or exosuits, resistance could be provided during movement. Equipping an exosuit with an FES-EMG system can reduce these adverse effects associated with living in space by providing the necessary stimulation to maintain muscle tone and bone density. Exosuits may also be utilised to provide exercise opportunities for patients suffering from other psychological conditions.

The exosuit may be helpful to astronauts in the microgravity environment in space. In space, exoskeletons are designed to enhance the physical abilities of the wearer. Particularly during extended space explorations such as spacewalks or deep space explorations, this could prove very

beneficial. Astronauts may benefit from this technology by being able to lift heavier objects, perform physically demanding tasks for extended periods of time, or jump higher in difficult environments. Furthermore, exosuits or exoskeletons may help reduce fatigue and injury risks associated with repetitive tasks. This is especially relevant for long-duration space missions where additional medical assistance may not be available.

Exosuits could also facilitate faster evacuations or more effective rescues in case crew members are injured or incapacitated in space. Integrated sensors in exosuits may provide real-time information about astronauts' health and fitness levels, which can be particularly useful for preventing overexertion or detecting potentially serious health problems at an early stage and for research purposes.

In future, exosuits and exoskeletons will likely be explored in space in addition to these applications. The unique challenges of the space environment, including microgravity, radiation, and the necessity of airtight seals, would require any such technology to be thoroughly tested and modified.

Exosuit technology can be applied to more than just space exploration. It can also be used for physical rehabilitation and physiotherapy on Earth. There are many applications of exoskeletons and exosuits on Earth for treating or assisting with paralysis, spinal cord injury, and muscle weakness. Exosuits could improve muscle strength and coordination for individuals recovering from injuries or strokes or living with conditions that affect their mobility. Each individual's progress and ability could be matched to the level of assistance the exosuit provides, thus allowing therapists to customise treatment plans. It is also possible to use the same sensors used for astronaut monitoring in space during therapy to provide accurate feedback to treatment plans and accelerate recovery by providing real-time feedback. In light of its dual-purpose nature, this technology is valuable in advancing our space exploration frontiers and improving our lives on Earth.

5.2 Future Work

The development of a lower limb exosuit for astronauts is a critical topic that holds great promise for the future of space exploration. Investigating and developing numerous areas is necessary to enhance the overall astronaut experience. We propose several research and development directions for the future within this context.

An interesting research area for designing an exosuit functionality involves a comprehensive kinematic study from an astronaut's perspective. A thorough understanding of the kinematics provides an exciting avenue for further exploration. As a result of studying and fine-tuning the complex movements and interactions between the exosuit and the astronauts' bodies, we can develop more comfortable and natural systems to move. A detailed kinematic analysis could reveal potential points of injury or stress, indicating areas of the design that require further modification or reinforcement. Motion capture technology and advanced computational modelling should be used in future research to develop a biomechanical model of the exosuit-astronaut system.

Further, integrating FES-EMG studies into exosuit development can lead to improved suit control and user feedback. The exosuit can offer more intuitive and responsive controls, effectively becoming an extension of the user's body, by recording and interpreting muscle signals via EMG. FES can also provide sensory feedback to astronauts while using the exosuit, providing a biofeedback loop that could improve proprioception and body awareness. A further study should be undertaken to develop and test FES-EMG integrated exosuits in simulated and microgravity environments.

These exosuits have limitations, including size, weight, and power efficiency, as well as limitations in terms of actuators. Another research frontier is the development of novel actuators. In the future, new technologies, including soft robotics and SMA or TCA, may offer new applications. With the help of soft robotic actuators, exosuits may be more flexible and lightweight, while shape-memory alloys may provide a superior power-to-weight ratio. A significant improvement in the functionality, comfort, and power efficiency of the exosuit could be achieved with these novel actuators.

As a final consideration, it would be beneficial to integrate artificial intelligence into the exosuit's system. Physical activities can be more effective using an intelligent exosuit that learns from astronaut movements, such as predicting and assisting with tasks. It could consist of simple, repetitive exercises and complex, highly precise tasks. Also, a machine learning-based system would be able to continually adapt to an astronaut's individual biomechanics and movement patterns, resulting in a personalized exosuit designed to fit the astronaut's needs.

Finally, it should be noted that the proposed future directions represent only the tip of the iceberg regarding space exploration exosuit development. By continuing to push the boundaries of kinematic study, FES-EMG integration, novel actuators, and AI integration, we can revolutionize how astronauts train and perform tasks, ultimately paving the way for more ambitious space missions. As a result of these technological advances, astronautics appears to have a bright future.

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