He Raraunga Inamata, He Toronga Ānamata, He Huanga Āke Tonu Atu: A Multifaceted Approach to Improving Quality of Life for Upper Limb Amputees

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Abstract

This thesis investigates innovative approaches to enhance the quality of life for upper limb amputees, integrating advanced prosthetic design, neurocontrol systems, and Māori knowledge systems. With the prevalence of prosthetic rejection and limitations in current designs affecting amputees' daily functionality and psychological well-being, a multifaceted strategy is essential. This research aims to address these challenges by improving prosthetic functionality, user control mechanisms, and incorporating cultural perspectives into prosthetic development.

The study first focuses on the design, development, and evaluation of four low-cost prosthetic hands. Assessing their Degrees of Freedom (DoF), Range of Motion (RoM), and Kapandji scores. The research proposes a novel hybrid coupled-tendon system. This system aims to combine the adaptability of underactuated designs with the precision control of coupled mechanisms, enhancing the prosthetic hands' functionality and grasp versatility.

In exploring control mechanisms, an EEG-based control system was developed to improve the intuitiveness of prosthetic control. Through comparative analysis of motor execution and action observation training regimes, facilitated by a digital twin, the study evaluates the efficacy of these methods in enhancing users' control over the prosthetics. The research identifies limitations in the classification of multiple active grasps and suggests potential improvements through augmented and virtual reality training environments.

This thesis incorporates Māori perspectives by examining how mātauranga Māori can inform and enrich prosthetic design and usage. Through the analysis of pūrākau Māori, this work highlights the importance of considering the mauri, whakapapa of materials in prosthetic manufacturing and the implications of tapu on control systems. This inclusion aims to create culturally resonant devices that acknowledge and integrate the spiritual and cultural dimensions of the user's identity, offering a holistic approach to prosthetic development.

This interdisciplinary research contributes to the field by proposing a comprehensive framework that not only advances prosthetic technology but also aligns with cultural values and practices. By addressing the technical, psychological, and cultural needs of upper limb amputees, the project underscores the potential of combining engineering innovation with cultural wisdom to significantly improve amputees' autonomy and well-being. The findings advocate for a more inclusive and holistic approach to prosthetic development, emphasizing the importance of user-centric design and cultural competency in enhancing the quality of life for individuals with limb loss.

Acknowledgements

"Ehara taku to i te toa taki tahi, ēngari he toa taki tini e"

"My success should not be bestowed onto me alone, as it was not individual success but success of a collective"

This is a whakataukī that resonates deeply within the essence of this research, reminding us that success is not an individual achievement but the culmination of efforts by many. This thesis, while a reflection of my journey, is equally a testament to the support, guidance, and belief bestowed upon me by a collective of remarkable individuals and institutions.

Firstly, my gratitude extends to my supervisors, Dr Mahonri Owen and Dr Martin Atkins, whose expertise, patience, and unwavering support have been the backbone of this research. Their guidance has been instrumental in navigating the complexities of this project, providing a steady hand and insightful feedback at every turn.

I extend my sincere appreciation to Ahuora, the University of Waikato, and Te Ati Hau Trust for their generous financial support and belief in the value of this work. Their commitment to advancing knowledge and innovation has been crucial in providing the resources necessary to undertake this research.

To those who reviewed this thesis, Ella Cameron-Smith, Te Hamua Nikora, and others who have lent their time and expertise. Your insights and constructive feedback have been invaluable in refining and strengthening this work.

I would also like to thank Te Hamua for gifting the title of this thesis "He raraunga inamata, he toronga ānamata, he huanga āke tonu atu." This translates to mean "Grasping the past, reaching to the future, getting results for ever." Playing on the grasping and reaching of the hand and arm, using ancient (Māori) and futuristic (modern engineering) to bring about a solution that lasts for all time. This is a taonga which greatly reflects the intention of this work.

Lastly, I extend my deepest thanks to my whānau. To my parents, whose endless support and wisdom have been my foundation and to Ruby and Tungane for putting up with me for the last year and keeping a roof above my head.

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Chapter 1: Introduction

Amputation represents a significant alteration in a person’s life. Amputation can arise for a multitude of reasons such as traumatic injuries, medical conditions like diabetes, or congenital differences.[2] The loss of a limb not only changes a person's physical capabilities but also deeply affects their psychological well-being and social interactions. Upper limb amputation imparts a significant impact to the amputee due to the role of the hands in day-to-day activities. The hands play a critical function in performing daily activities, from basic self-care tasks such as dressing and eating to complex interactions with technology and the environment. Consequently, the loss of an upper limb often leads to a marked decrease in independence, challenging the individual's ability to live a self-sufficient life and participate fully in society.

The advent of prosthetic technology has heralded a new era of hope for upper limb amputees, offering mechanisms to regain lost independence and functionality. Prosthetic devices have evolved significantly, transitioning from simple cosmetic replacements that offer minimal functional benefits to sophisticated myoelectric and robotic systems[3]. These advanced prostheses aim to replicate the natural movements of the human hand and arm, incorporating sensors, motors, and artificial intelligence to provide users with a range of motions and grips that closely mimic those of a biological limb.

Despite these technological strides, the practical usage of upper limb prosthetics remains fraught with challenges. The complexity of human hand movements, combined with the intimate connection between bodily function and personal identity, makes designing prosthetic devices that fully meet amputees' needs a significant challenge. Users frequently encounter issues related to the comfort, control, and overall integration of these devices into their daily lives which often result in the rejection of prosthetic limbs[2].

Prosthesis rejection can occur for a variety of reasons, ranging from the physical aspects of the device, such as discomfort and lack of intuitive control, to psychological barriers, including the acceptance of the prosthesis as part of one's body image[2]. Studies indicate that rejection rates for upper limb prosthetics can be as high as 30-45%, underscoring a significant disconnect between the capabilities of current prosthetic technology and the needs and expectations of its users[4]. The effects of rejection are not only emotionally and psychologically taxing on the individual but also financially taxing as upper limb prostheses can cost up to $75,000 NZD[5]. This further emphasises the need for a more user-centric approach in prosthetic design and rehabilitation processes.

This thesis sets out to address these challenges to enhance the quality of life for upper limb amputees through a multifaceted approach that includes improving prosthetic function, advancing control mechanisms, and integrating Māori perspectives into prosthetic design and usage.

1.1 Aim

The aim of this research is to explore convergent prosthetic technology to improve the quality of life for upper limb amputees. Achieving this aim requires a multifaceted strategy that addresses the complex needs of amputees, from the physical to the psychological and cultural. The objectives of this thesis are structured around three key goals: improving the function of prosthetic hands, improving the user's ability to control their prosthesis, and exploring the value of the mātauranga Māori perspective.

1.1.1 Improving the function of prosthetic hands

The design and evaluation of prosthetic hands stand at the forefront of this objective. By focusing on developing prosthetic devices that offer greater functionality, durability, and ease of use, this research aims to bridge the gap between the current capabilities of prosthetic technology and the real-world needs of amputees. Through rigorous testing and refinement, the project seeks to introduce prosthetic hands that amputees can rely on for a wide range of daily activities.

1.1.2 Improving the users ability to control their prosthesis

The usability of any prosthetic hand is determined by the user's ability to control it intuitively and effectively. This thesis explores the development of a brain control system that leverages electroencephalography (EEG) technology to create a direct interface between the user's neural activity and the prosthetic device. Additionally, the design of a comprehensive training regime aims to equip users with the skills and confidence needed to harness this control system, ensuring they can maximise the potential of their prosthetic limbs.

1.1.3 Exploring the value of the mātauranga Māori

Recognising the importance of cultural dimensions in the acceptance and use of prosthetic devices, this research embarks on an exploration of Māori knowledge systems. By integrating Māori perspectives into the design and application of prosthetics, the project seeks to create devices that are not only functionally effective but also culturally resonant. This approach acknowledges the diverse needs and identities of amputees, aiming to provide solutions that honour their heritage and contribute to a sense of wholeness.

This thesis represents a convergence of engineering, neuroscience, and cultural studies, aiming to push the boundaries of what is possible in prosthetic technology. By addressing the technical challenges associated with prosthetic design and control and embracing the cultural insights provided by Māori knowledge systems, this research endeavours to make a meaningful impact on the lives of upper limb amputees. Through this holistic approach, the project aims to improve prosthetic devices functionality

and enhance the overall well-being of those who use them, marking a significant step forward in the quest to improve quality of life for amputees.

1.2 Thesis Structure

The structure of this thesis is organized into several chapters, each dedicated to a specific facet of the overarching aim to enhance the quality of life for upper limb amputees.

Chapter 2 commences with an extensive literature review, segmented into three sections: prosthesis design, control systems, and the contributions of mātauranga Māori to the domain of prosthetics. This comprehensive review sets the foundation for the subsequent chapters.

Chapter 3 presents the design and subsequent evaluation of four electromechanical upper limb prostheses. This chapter not only elaborates on the engineering challenges and solutions but also assesses the prostheses' functionality and user-centric benefits.

Chapter 4 outlines the development and implementation of an EEG-based control system. It further explores various training regimes, aiming to optimize the user's ability to effectively control the prosthetic devices through brain-computer interfaces.

Chapter 5 ventures into the realm of mātauranga Māori, examining how traditional Māori knowledge, particularly pūrākau and whakapapa, can be applied to the field of prosthetics. This chapter delves into the implications of integrating mātauranga Māori into prosthetic design and user experience, highlighting a unique perspective on rehabilitation and technology.

Chapter 6 highlights the key findings, discussions, and presents conclusions drawn from the research conducted across the preceding chapters. It consolidates the insights gained and outlines potential directions for future research.

To assist in the clarity and comprehension of the thesis, a glossary is included at the end, defining technical terms, Māori terms, and abbreviations utilised throughout the document.

Chapter 2: Literature Review

2. 1 Introduction

This review comprehensively explores the multifaceted domain of prosthetic technology. The scope of this review is categorised into three primary sections: prosthetics, control systems, and mātauranga Māori, each contributing unique insights and advancements in the field of rehabilitation and prosthetic development.

The first section delves into the realm of prosthetics, examining the implications of upper limb amputation on an individual's daily life and overall well-being. It begins by exploring the anatomy of the hand, laying the foundation for understanding the challenges and requirements in prosthetic hand design. Following this, the review categorises the various types of prosthetics available, ranging from traditional devices to advanced myoelectric and bionic prosthetics. It emphasises their design, functionality, and the technological advancements that have shaped their evolution. Furthermore, the section addresses the concept of grasping, discussing how different prosthetic designs facilitate this essential movement and how they compare in terms of effectiveness and user satisfaction.

The second section focuses on prosthetic control systems, highlighting the technological underpinnings that enable sophisticated interaction between the user and a prosthetic device. It covers ElectRoMyography (EMG) as the prevalent method for harnessing bioelectrical signals from muscle movements to control prosthetic limbs. The review expands into Electroencephalography (EEG), a technique that leverages brain activity for prosthetic control. Furthermore, this segment addresses the role of rehabilitation in adapting to and effectively using these advanced prosthetic systems.

The final section introduces mātauranga Māori, a unique perspective on health, disability, and rehabilitation grounded in Māori knowledge and principles. It presents the Māori perspective of health through models such as Te Whare Tapa Whā and Te Wheke, which emphasise a holistic approach to well-being encompassing physical, mental, spiritual, and familial dimensions. This review also explores the Māori perspective of disability, challenging conventional perceptions and highlighting the value of inclusivity and community support. Lastly, this section discusses the application of mātauranga Māori in rehabilitation practices, illustrating how integrating these cultural insights can enhance the rehabilitation process and support the reintegration of individuals with amputations into their communities.

Through the exploration of these three categories, this review aims to illuminate the interdisciplinary approaches in the development and application of prosthetic technologies, the advancement of control systems, and the integration of indigenous knowledge in rehabilitation, contributing to a more holistic and inclusive understanding of upper limb prosthetic adoption and adaptation.

2.2 Prosthesis Design

2.2.1 Upper Limb Amputees

Upper limb amputations encompass a range of conditions, from the loss of fingers to the amputation of the entire arm. The prevalence of upper limb amputation varies globally, influenced by factors such as traumatic injuries, vascular diseases, cancer, and congenital conditions[6]. While exact statistics fluctuate across regions and over time, it is estimated that upper limb amputations account for approximately 30% to 45% of all amputations[2, 4]. The impact of such amputations is profound, affecting not only the physical capabilities of individuals but also their psychological well-being and social integration. Rehabilitation and the provision of prosthetic devices are crucial for restoring function and improving the quality of life for amputees.

Despite advances in prosthetic technology, the rejection rates for upper limb prostheses remain a significant concern. Rejection, in this context, refers to the discontinuation of prosthetic use by the amputee, often due to factors such as discomfort, lack of functionality, or psychological reasons. Studies indicate that rejection rates can vary widely, with some reports suggesting that up to 45% of upper limb amputees do not regularly use their prosthetic devices[2]. The reasons for rejection are multifaceted, encompassing issues related to the prosthetic fit, weight, appearance, and the degree to which the device meets the functional needs and expectations of the user. In addition, the psychological impact of limb loss and subsequent prosthetic use, including issues of body image and social stigma, can further influence the acceptance and long-term use of prosthetic limbs[7].

2.2.2 Anatomy of the hand

The complexity of the human hand is underscored by its anatomy. The human hand is assembled of 27 bones, interconnected through an elaborate network of joints and ligaments, facilitating the hand's dynamic range of motion (RoM) and dexterity. The hand has four fingers, each comprising three phalanges. These bones articulate through three principal types of joints: the metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints, enabling the nuanced movements essential for complex grasping and manipulation tasks. The thumb has two bones that operate through the interphalangeal (IP) and MCP joints[8, 9]. Figure 1 shows the bones and the joints that form the structure of the hand.

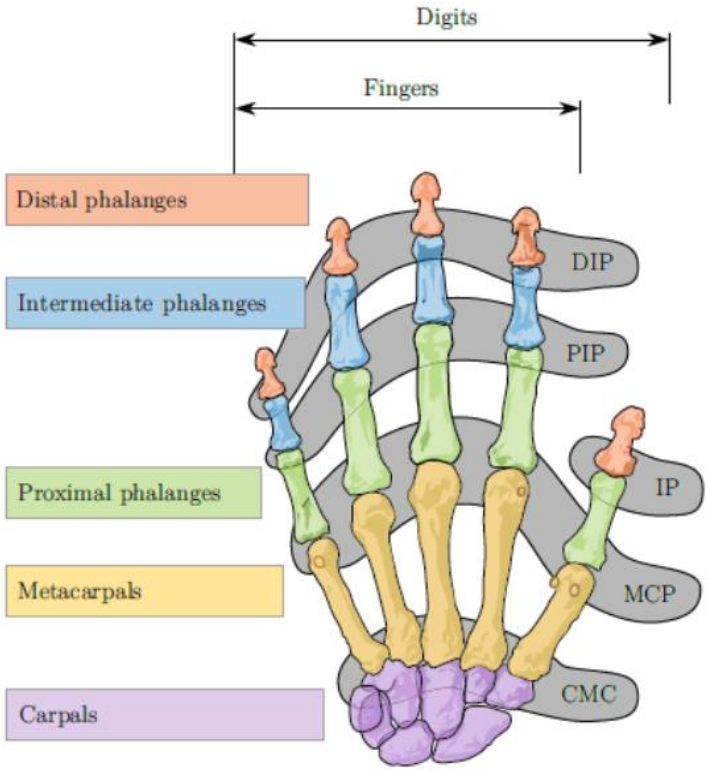

Figure 1: Bone structure of the human hand[5]

The palmar region of the hand houses the metacarpals, five elongated bones that extend from the intricate carpals of the wrist to the base of the fingers. This structural arrangement not only stabilises hand movements but also forms the foundation for the hand's arches, enhancing its ability to conform to and manipulate objects. The wrist is constituted by eight small carpal bones that serve as the junction between the hand and the forearm, accommodating a wide RoM while maintaining the structural integrity necessary for the transfer of forces during hand activities. Supporting this bone architecture, a complex array of ligaments ensures joint stability and facilitates motion, enabling the hand to perform its diverse functions efficiently[10, 11].

2.2.3 Types of Prosthetic Hands

The design and functionality of prosthetic hands have evolved throughout history. A range of solutions tailored to the diverse needs and preferences of users are offered. These prosthetic devices can be categorised into three main types: passive, body-powered, and electromechanical. Each type presents unique characteristics, advantages, and challenges, which are crucial to understand for both users and developers.

2.2.3.1 Passive Prosthetics

Passive prosthetics are non-actuated devices designed primarily for aesthetic purposes, mimicking the appearance of a natural hand. These prosthetics do not offer active movement but are valued for their

ability to enhance the user's appearance and boost self-confidence by reducing social stigmatism. They are often made to match the user's skin tone and may include details such as nails and lifelike textures. Key advantages of passive prosthetics include their lightweight design, affordability, and simplicity, making them an accessible choice for many amputees seeking to restore their body image without the need for functional replacement[3]. Figure 2 shows an example of a silicone passive hand prosthesis.

Figure 2: Cosmetic silicone passive hand prosthesis [3]

2.2.3.2 Body-Powered Prosthetics

Body-powered prosthetics are mechanical devices that harness movements from other parts of the user's body, such as the shoulders or residual limb, to control the prosthetic hand or arm. A common configuration involves a harness and cable system where the user performs specific movements, such as extending the shoulder, opening or closing the prosthetic hand, or operating a split hook. This design, first introduced in 1818, remains popular due to its reliability, low cost, and ease of maintenance. While these prosthetics are typically less anthropomorphic in appearance compared to their passive and electromechanical counterparts, they provide valuable manipulation capabilities and can be highly efficient for manipulation tasks [3]. The split hook, for example, though not lifelike in appearance, is renowned for its durability and functionality, as shown in Figure 3.

Figure 3: Split hook terminal device[3]

2.2.3.3 Electromechanical Prosthetics

Electromechanical, or myoelectric, prosthetics represent the cutting edge in prosthetic technology, featuring electric motors powered by batteries to achieve movement. These devices are designed to mimic the natural motion of the human hand, offering a high degree of dexterity and functionality. They are typically anthropomorphic, closely resembling the appearance of a natural hand, and can perform a wide range of movements from grasping to pointing. The control of these prosthetics is achieved through sensors that detect muscle contractions in the residual limb, which are then translated into movements by the prosthetic's motors. Although electromechanical prosthetics are the most advanced and functional option available, they are also the most expensive and complex, requiring sophisticated control systems and regular maintenance. Despite these challenges, the potential for improved quality of life they offer makes them a highly sought-after solution for many amputees[3, 12, 13]. Figure 4 depicts the Ottobock BeBionic electromechanical prosthetic hand.

Figure 4: Ottobock BeBionic prosthetic hand[14]

The growing popularity of electromechanical prosthetic hands has led to increased scrutiny and evaluation of these devices. Owen's (2015) review provides an overview of available electromechanical hands, focusing on key aspects that define high-quality artificial hands. Some aspects are Degrees of Freedom (DoF), drive mechanism, and actuator type [5]. Deshpande, Xu et al. (2011) also contribute to this field by reviewing artificial hands and identifying important design features. In general, a simpler hand design corresponds to a lower DoF [15]. The DoF of an artificial hand represents the independent parameters that define its configuration.

An artificial hand's ability to function effectively in a natural human environment is directly related to its resemblance to the human hand[15]. When designing anthropomorphic artificial hands, the DoF serves as a measure of their functionality. Studies modelling the human hand suggest that an accurate representation requires twenty-four DoF, including the wrist [16]. However, most literature agrees on twenty-one DoF, excluding the wrist. Other research suggests similar ranges, stating between twenty-one and twenty-six DoF [17]. Essentially, the closer the DoF of an artificial hand is to that of a human hand, the greater its potential to function in an unmodified human environment. Table 1 outlines the DoF and drive mechanisms of commercially available electromechanical prosthetic hands.

Table 1: Degrees of freedom (DoF) of commercially available prosthetic hands[5]

Hand	DoF	Actuators	Under-actuated	Self-contained	Drive Mechanism
I-limb	6	DC Motor	Yes	Yes	Rigid Link
BeBionic	5	DC Motor	Yes	Yes	Rigid Link
Dextrous	6	DC Motor	Yes	Yes	Tendon Driven
Robonaut	12	DC Motor	Yes	Yes	Tendon Driven
Shadow	20	Air Muscle	No	No	Tendon Driven
Utah/MIT	15	Pneumatic	No	No	Tendon Driven
Hitachi	12	Memory Alloy	No	No	Tendon Driven
Biomimetic hand	21	DC Motor	Yes	No	Tendon Driven
Belgrade	4	DC Motor	Yes	No	Rigid Link
Stanford/Salisbury	9	DC Motor	Yes	No	Tendon Driven
NTU	17	Micro-motor	No	Yes	Tendon Driven
DLR	13	DC Motor	No	Yes	Gears
Michelangelo	17	DC Motor	Yes	Yes	Rigid Link

In addition to this, DoF plays a crucial role in the context of grasping. The number of independent parameters that define the configuration of an artificial hand directly influences its ability to perform grasping motions with dexterity and precision. A higher number of DoF in an artificial hand allows for a greater range of finger movements and joint articulations, closely resembling the flexibility and adaptability of the human hand. This increased freedom of movement enables the artificial hand to achieve more versatile and effective grasping strategies, enhancing its capacity to manipulate objects with various shapes, sizes, and textures. Thus, the alignment of DoF in an artificial hand with those of the human hand is vital for optimizing its grasping capabilities and facilitating natural and efficient interactions with the surrounding environment [16].

2.2.4 Grasping

Grasping can be defined as the act of securely holding or gripping an object using the hand or fingers. It involves the coordination of muscles, tendons, and joints to apply appropriate force and position the hand in a way that ensures a stable and controlled grip on the object. The ability to grasp is fundamental for various everyday tasks, such as writing, eating, using tools, and performing intricate manual tasks. Feix et al. defines a grasp as “every static hand posture with which an object can be held securely with

one hand, irrespective of hand orientation"[18]. In the realm of grasp taxonomy, early advancements were made in 1989 by Cutkosky, who identified and classified everyday tasks associated with grasping[19]. Subsequent research by Feix, Pawlik et al. in 2009 further refined this taxonomy by proposing seventeen distinct grasp types encompassing a broad range of hand configurations [20]. Supporting this notion, Feix, Romero et al., in 2016, systematically organized the existing literature, consolidating various grasp types into a manageable set of categories[18]. This systematic categorisation aids researchers in comprehending and analysing the intricacies of different grasping actions and their underlying principles.

The GRASP Taxonomy offers a detailed classification of human hand grasps, encompassing 33 specific types that are static and stable, performed with one hand. It organises these grasps according to four main criteria: opposition type, virtual finger assignments, grasp nature, and thumb position. Opposition type delineates how force is applied between the hand and the object, highlighting the various ways in which the thumb and fingers can oppose each other or the object to secure a grip. Virtual finger assignments group fingers that work together as a single functional unit based on the direction of applied force, simplifying the analysis of complex finger coordination. The nature of the grasp is categorised as either power, intermediate, or precision, indicating the grasp's intended use, from strong, forceful grips to delicate, controlled manipulations. Lastly, the position of the thumb is defined as abducted or adducted. This taxonomy not only aids in understanding the intricacies of human hand function but also informs the design and development of prosthetics, robotic hands, and ergonomic tools by closely replicating the human hand's capabilities [18]. The GRASP Taxonomy can be found in Appendix 1.

2.3 Control Systems

2.3.1 Biological Signal Generation

2.3.1.1 The Human Brain

The human brain, a marvel of biological engineering, stands as the epicentre of complex functions, orchestrating the myriad of activities that define human life. It is responsible for controlling the body, processing sensory information, and enabling cognitive functions such as thought, memory, and emotion [21].

The brain is divided into several major sections, each with specific function as shown in Figure 5. The cerebrum is responsible for cognitive functions and voluntary actions. The cerebellum coordinates movement and balance, while the brainstem controls essential involuntary functions like breathing and heart rate. The limbic system, encompassing structures such as the hippocampus and amygdala, regulates emotions and memory [21, 22].

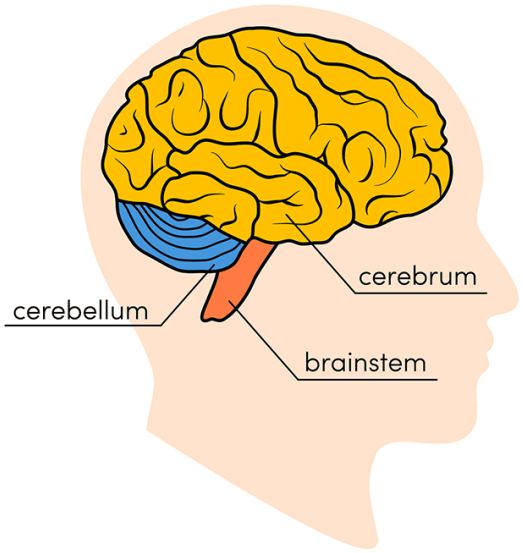

Figure 5: Sections of the brain

Neurons are the fundamental units of the brain and nervous system, specialised cells that transmit information via electrical and chemical signals. Each neuron can connect with thousands of others, forming complex networks that underlie brain functions. Neurons generate electrical energy through the movement of ions across their membranes, creating a difference in electrical charge known as the membrane potential. The brain's production of electrical energy and its orchestration of neuronal activity are central to the functioning of the nervous system [21-23].

2.3.1.2 The Nervous System

The nervous system is a sophisticated network that coordinates the body's sensory and motor information. It is divided into two main components: the Central Nervous System (CNS) and the Peripheral Nervous System (PNS)[24].

The CNS consists of the brain and spinal cord, serving as the control centre for processing and interpreting sensory information and issuing commands to the body. In contrast, the PNS extends beyond the CNS, with nerves and neurons that connect the CNS to limbs and organs. The PNS is divided into the somatic nervous system, which controls voluntary movements, and the autonomic nervous system, which regulates involuntary functions [24, 25].

Motor nerves are a part of the PNS and play a key role in initiating and controlling muscle movements. They transmit action potentials (AP), which are rapid changes in the electrical charge of a nerve's membrane from the CNS to muscles, prompting them to contract or relax[25].

The AP carried by motor nerves result in the release of neurotransmitters at neuromuscular junctions, triggering muscle fibres to activate and produce movement. This process is fundamental to all voluntary muscle actions, from simple gestures to complex coordinated activities [26, 27].

2.3.2 Biological Signal Detection

2.3.2.1 Electromyography (EMG)

EMG is a method of measuring muscle response or electrical activity in response to nerve stimulation of the muscle. Most upper limb prosthetics on the market today utilize an EMG control system. To produce a muscular force, muscle fibres must receive an electric impulse from a nerve called a motor neuron. Once activated by the CNS, an electrical impulse propagates down the nerve to each motor endplate. At this specialized synapse, ionic events occur that culminate in the generation of muscle fibre movement, called an action potential[26, 28].

Even at rest, muscle is excitable and electrical activity can be recorded. Normally, the inside of the muscle fibre has an electrical potential of about –90mV but can be altered with exercise. The voltage gradients are from the presence of three ions: Sodium (Na+), Potassium (K+) and Chloride (Cl-). Of these, the concentration of Na+ is more permeable in some types of muscle, especially slow twitch fibre [26].

The AP is the neural messenger responsible for activating every segment of the muscle fibre. So that each sarcomere contributes to the generation of muscular force. The process begins with a change in permeability to Na+ sodium ions. Sufficient Na+ ions enter the muscle cells to reverse the polarity of the membrane potential so that the inside of the muscle fibre becomes positive by about 30mV. Simultaneously, K+ permeability changes and these ions exit the cell [26-28]. Figure 6 displays the MyoBand EMG sensor and the signals generated from the sensors.

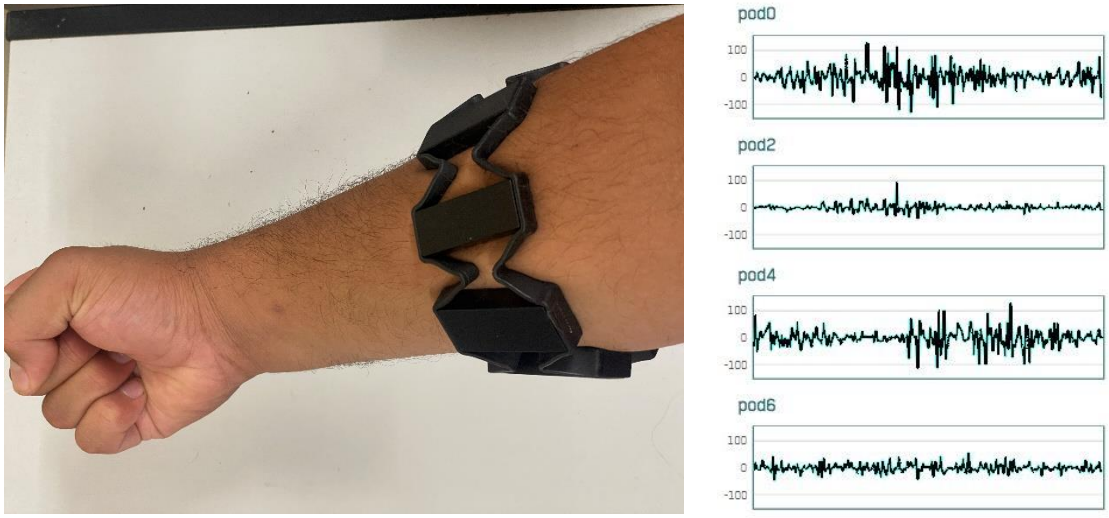

Figure 6: MyoBand EMG sensor

2.3.2.2 Electroencephalography (EEG)

EEG is a technique for recording and interpreting the electrical activity of the brain. Nerve cells within the brain generate electrical impulses that rhythmically fluctuate in distinct patterns. This process allows for a means of studying the workings of the brain and the connections between the brain, CNS and muscle groups [29].

Typically, brain activity data is gathered using a non-invasive neural headset with electrodes mounted to the user's scalp. Some of the commercially available headsets include Emotiv insight, EMotiv EPOC+, Neurosky Mindware. These can range in price from $170 - to $3000 depending on the number of electrodes/channels available[30]. Another consideration is software. For the data to be interpreted and processed correctly, a brain-computer interface (BCI) software is required. Emotiv has developed their own BCI software, Emotiv BCI-OSC. This software allows users to train mental commands and view raw data, and the open sound control addition allows for real-time control of multimedia processors[29]. Figure 7 displays the Emotiv Insight neural headset.

Figure 7: Emotiv Insight neural headset

While the prosthetics industry has yet to shift to EEG as a commercial control method, they can be benefits to using this system. In some instances, an amputee may have suffered nerve damage resulting in inaccurate EMG signal data; in this case, an EEG system would be better suited. This is a non-invasive technique that can serve as a powerful aid for severely disabled people in their daily lives [31].

2.3.2.3 Lightmyography

Lightmyography (LMG) is a relatively new control scheme that holds a lot of promise for the field of upper limb prosthesis control. LMG systems utilise light emitting diodes (LEDs) to project light through a silicone layer onto the skin surface[32]. Photodetectors positioned adjacent to these LEDs capture the light that is reflected. Muscle movements, such as those involved in making a grasp, alter the physical state of the muscle. Consequently, the surrounding tissue and the silicone layer resting on the skin is also affected. These alterations lead to changes in the intensity of light that the photodetectors register. By employing sophisticated machine learning techniques, the variations in light intensity captured by the photodetectors are analysed. This allows for interpretation the specific grasp being made or to gauge the level of force being applied by the user.

This technology offers a significant advantage over traditional electromyography (EMG) control systems by eliminating electrical noise, thereby enhancing signal clarity. Furthermore, LMG facilitates proportional control, allowing for fine-tuned adjustments in the force output, which is an important aspect in creating more natural and responsive prosthetic devices.

Despite its emergence in recent years, this technology has seen practical application in prosthetic hand control as demonstrated by Shahmohammadi et al[33]. This innovative work integrates this control system into a prosthetic hand capable of recognising an array of 32 distinct hand gestures. Of these, 10 gestures have been successfully decoded and translated into corresponding movements by the prosthetic hand, showcasing the potential of Light Myography (LMG) in enhancing the functionality and adaptability of prosthetic devices. This breakthrough not only marks a significant advancement in prosthetic technology but also opens new avenues for research and development in the field of assistive devices.

2.3.3 Rehabilitation processes

The training of EEG-controlled prosthetic systems employs a variety of methods to harness and interpret the user's neural signals for precise device manipulation. These methods leverage the brain's innate capabilities, translating thought and observation into actionable commands for prosthetic control. Among the most effective training strategies are motor imagery, motor execution, action observation, and the application of the mirror neuron system.

2.3.3.1 Motor Imagery

Motor imagery involves the user mentally simulating a specific action without any physical movement [34]. This process engages the same neural pathways activated during the actual execution of the movement, making it a powerful tool for training the brain to control prosthetic devices. By imagining the movement, users can generate distinct EEG patterns that the system can learn to recognise and associate with specific prosthetic commands [35].

2.3.3.2 Motor Execution

Motor execution requires the user to physically perform the movement with their intact limbs, generating real motor actions that produce clear, measurable EEG signals. This method directly engages the motor cortex, producing robust neural patterns that can be captured and classified[36]. The advantage of motor execution lies in its ability to provide concrete examples of the desired action, aiding the system in accurately mapping these neural signatures to corresponding prosthetic movements[37].

2.3.3.3 Action Observation

Action observation training capitalizes on the brain's mirror neuron system, which is activated when performing an action and when observing someone else execute the same action[38]. This method allows users to watch a digital twin or another person perform the desired movements, triggering neural activity similar to that of actual movement execution. Action observation offers a less physically demanding training option, making it accessible to users with severe mobility limitations[39, 40].

2.3.3.4 Mirror Neuron System

The mirror neuron system underlies the effectiveness of action observation by providing a neural basis for learning and mimicking observed actions. These neurons fire when an individual acts and when they

observe the same action performed by others, facilitating the cognitive process of translating visual information into motor commands[41]. The engagement of the mirror neuron system in training protocols enriches the user's ability to control the prosthetic device through observed actions, enhancing the adaptability and responsiveness of the EEG-controlled system[39].

Collectively, these training methodologies contribute to the development of a highly responsive and user-centric EEG-controlled prosthetic system. By combining these approaches, researchers and developers can tailor the training process to the user's specific needs and capabilities, optimizing the system for improved performance and a more natural prosthetic experience.

2.3.3.5 Digital Twinning

Digital Twinning has been become an important tool in the rehabilitation process of upper limb amputees. Digital twinning refers to the creation of a virtual replica that accurately reflects the structure, dynamics, and functionalities of a physical system within a digital framework[42]. This concept bridges the physical and digital worlds, allowing for real-time monitoring, analysis, and simulation of the physical counterpart. Digital twins leverage data from sensors and operational data to simulate the current state of their physical twins accurately. This simulation capability enables predictive analysis, optimization, and decision-making processes by foreseeing the outcomes of various scenarios and actions without impacting the actual physical entity.

Recent advancements have seen the development of digital twins specifically tailored for prosthetic hand systems. These have typically been designed with the aim of user training and rehabilitation. These digital twins fall under one of three categories; on-screen, virtual reality (VR) or augmented reality (AR). A systematic review by Toledo-Peral et al. conducted in 2022 suggests that 57.5% of digital twin EMG control systems are run through virtual reality and 10% use augmented reality as an interface[43]. A study by Hao et al. was conducted to evaluate the feasibility of an augmented reality prosthetic hand rehabilitation digital twin and compared the performance to a traditional on-screen digital twin[44]. The results of this study indicate that all participants agreed that the augmented reality digital twin was more immersive and the resulted in a higher task completion rate. However, the participants also tended to take longer to complete the task than in the on-screen digital twin.

2.4 Mātauranga Maori

2.4.1 Māori Perspective of Health

The Māori perspective on health offers a holistic view, emphasising the interconnectedness of various aspects of well-being. This perspective is encapsulated in several indigenous health models, among which Te Whare Tapa Whā, Te Wheke, Te Whare o Oro, Wairua Theory stand out for their comprehensive approach to health and well-being. The proceeding section will outline these models and discuss the ideas each model is founded on.

2.4.1.1 Te Whare Tapa Whā

Developed by Sir Mason Durie, Te Whare Tapa Whā is a seminal Māori health model that employs the analogy of a wharenui (meeting house) to represent the four dimensions of health [40]. This model articulates that just as the four walls of a wharenui support its structure, the four dimensions of health support a person's overall well-being. These dimensions are:

- Taha Tinana (Physical Health): The cornerstone of well-being, representing the physical body and its needs.
- Taha Wairua (Spiritual Health): The unseen and unspoken energies that influence well-being, including faith and belief systems.
- Taha Hinengaro (Mental and Emotional Health): Cognitive and emotional aspects, encompassing thoughts, feelings, and behaviours.
- Taha Whānau (Family and Social Health): Social well-being, focusing on relationships and community connections.

Durie's model suggests that optimal health can only be achieved when all four dimensions are in balance. If one aspect is neglected or damaged, it impacts the others, leading to imbalance and illness [45, 46]. Figure 8 shows the walls of Te Whare Tapa Whā.

Figure 8: Te Whare Tapa Whā framework of Māori wellbeing

2.4.1.2 Te Wheke

Te Wheke was conceptualized by Dr. Rangimarie Turuki Rose Pere and further expands on the Māori approach to health[47]. Drawing on the octopus as a symbol, this model represents the wholeness of a person and their environment. Each of the eight tentacles signifies a different dimension of selfhood and well-being, with the suckers on each tentacle representing the various aspects within each dimension. The dimensions include:

- Wairua (Spirit)
- Mana Ake (Unique Identity)
- Mauri (Life Force)
- Whanaungatanga (Relationships)
- Tinana (Physical Health)
- Hinengaro (Mental Health)
- Whatumanawa (Emotional Well-being)
- Ha a Koro Ma, a Kuia Ma (Breath of Life from Ancestors)

The interconnected and inseparable nature of these dimensions is symbolised by the intertwining tentacles, emphasising that each aspect of a person's life is integral to their overall health and well-being [47, 48].

2.4.1.3 Te Whare o Oro

Te Whare o Oro is a te ao Māori framework representing the development of the brain and its functions. This model builds upon Te Whare Tapa Whā and defines more sections of the wharenui [1]. The addition of four pou (pillars) is used to reflect the foundational structures of the brain.

Pou Tuarongo represents the brainstem, the foundational pillar that connects the brain to the spinal cord and regulates vital life-sustaining functions such as breathing, heart rate, and blood pressure. In the context of Te Whare o Oro, the Pou Tuarongo underscores the essential nature of these basic physiological processes, grounding the individual's existence and well-being in the physical realm.

Pou Tāhū symbolises the diencephalon and cerebellum, key components involved in processing sensory information, maintaining homeostasis, and coordinating movement and balance. This pillar emphasises the integration and harmony of bodily functions, reflecting the interconnectedness of the individual with their environment and the importance of maintaining equilibrium within oneself.

Pou Tokomanawa, representing the limbic system, is central to the framework, much like the heartwood that supports the structure of the wharenui. It is associated with emotions, memory, and attachment, highlighting the critical role of feelings and relationships in shaping an individual's experience and interaction with the world. This pillar draws attention to the emotional and social dimensions of well-being, acknowledging their profound impact on mental health.

Finally, Pou Kaiāwhā corresponds to the cerebral cortex, the outer layer of the brain responsible for higher-order functions such as thought, language, consciousness, and creativity. This pillar celebrates the capacity for knowledge, reflection, and innovation, recognising these abilities as fundamental to human identity and cultural expression. Figure 9 shows the adapted wharenui of Te Whare o Oro [1].

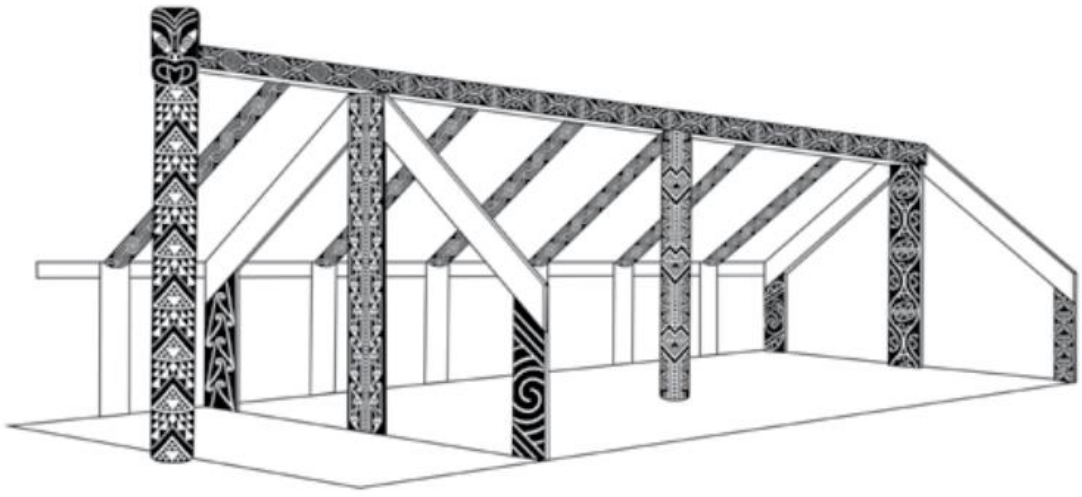

Figure 9: Te Where o Oro framework of Māori brain health[1]

2.4.1.4 Wairua Theory

The wairua theory of traumatic brain injury (TBI) in young Māori proposes that when a physical injury occurs a culturally defined injury occurs simultaneously [49, 50]. This injury is proposed to occur to wairua, a Māori specific expression of the interconnectedness between people and the universe, sometimes also translated as the spiritual dimension of being [51]. This theory underscores the importance of addressing not only the physical trauma but also the cultural and spiritual dimensions to facilitate a comprehensive recovery for both the individual and their whānau.

Expanding the scope of this perspective, when considering the experience of amputation, a similar interplay between physical and cultural dimensions becomes apparent. Amputation is not merely a loss of a body part; it carries profound cultural and spiritual implications, disrupting one's sense of self and place in the broader context of life.

Interestingly, just as there was a gap in assessing the extent of culturally defined injury in TBI, a similar gap may exist in the literature regarding the cultural dimensions of amputation within the Māori cultural framework.

2.4.2 Māori Perspective of Disability

2.4.2.1 Traditional Perspective

The traditional Māori viewpoint of disabilities challenges conventional Western thinking, presenting a unique perspective that diverges from the more common deficit-based models. King illuminates this distinctive outlook, emphasising that individuals with impairments were not only acknowledged but revered for their exceptional abilities, often elevated to a god-like stature within the community [52]. In this paradigm, the focus shifts away from what individuals lack to accentuating their remarkable capabilities, challenging prevailing societal notions and highlighting the cultural context's significance in shaping perceptions of disability.

Central to this perspective is the notion of individuals with disabilities being considered special, revered ones imbued with tapu, a sense of the sacrosanct [53]. This perspective, described by Jim Williams (2015) as being "touched by the gods," is exemplified through historical examples that challenge conventional definitions of disability[52]. For instance, the Māori term "kāpō," referring to blindness, was not considered a disability in the traditional sense. Instead, it was seen as a tohu, or sign, of greatness. Kāpō individuals were perceived as powerful, relying on heightened abilities in their remaining senses. The mythological figure Maui Tikitiki a Taranga, a renowned hero and trickster, had a blind grandparent, Murirangawhenua, who was revered for knowledge and wisdom. Murirangawhenua's cloudy vision was considered a source of strength, as demonstrated by the gift of the jawbone to Maui for creating a fishhook pivotal to Polynesian mythology [52, 54].

Similarly, within the Tainui iwi, the great chief Hape, acknowledged as one of the founders of the tribe, had talipes equinovarus or 'club foot.' Despite this, his condition did not detract from his status as a rangatira, or great chief. Notable chiefs like Te Rangihaeata of Ngāti Toa iwi also had clubfoot, but little emphasis was placed on the disability; rather, it was seen as a harbinger of greatness[52].

The perspective extends beyond cultural figures to contemporary examples like Stevie Wonder. Despite his visual impairment, Stevie Wonder's immeasurable influence on global music challenges conventional perceptions of disability. This prompts reflection on whether prioritising a deficit view of disability is damaging and whether a focus on what individuals can achieve, drawing upon their heightened senses, is more constructive. Aligning with the holistic Māori worldview, this perspective underscores the importance of addressing spiritual, social, and mental dimensions alongside physical loss due to disability or amputation. Moreover, the application of mātauranga Māori demonstrates its capacity to describe and understand complex knowledge from a Western perspective.

2.4.2.2 Modern Perspectives

In the evolution of Māori perspectives on disability, the changing times have given rise to modern interpretations that converge with the enduring impacts of colonisation. Indigenous disabled individuals confront experiences and challenges distinct from their non-indigenous counterparts, stemming from ongoing colonisation and intersecting forms of oppression, including racism-induced discrimination [55]. The concept of "colonization as the primary disability," articulated by Bray and Kingi (2000), underlines how colonising experiences have perpetuated indigenous disablement, reinforced the dominance of the mainstream culture and contributing to the disconnection from ancestral lands post-colonization [56]. Such disconnection, in turn, directly influences the health of wairua (spiritual well-being).

This contemporary discourse challenges the adequacy of both medical and social models in explaining the nuanced experiences of indigenous disability [57]. In the evolving landscape of Māori perspectives on disability, two distinct interpretations have emerged, encapsulated by the terms Hauā and Whanau Hauā and Tāngata Whaikaha Māori. The term "Hauā," meaning "Crippled or lame," offers a uniquely Māori perspective on impairment, where some individuals acknowledge the physical aspect of their disability, while for many, the physical element is not the primary focus. The concept of "Whānau Hauā," denoting families with disability, acts as an umbrella term encompassing the diverse winds that propel whanau with disabled members. These winds, influenced by the mood of Tawhiri-matea, symbolise an environment that can quickly become unstable, making it challenging for whanau to achieve balance [57].

In addition to Hauā and Whanau Hauā, the term "Tāngata Whaikaha Māori" represents another facet of the modern Māori framework. This term serves as an umbrella descriptor for disabled Māori or those

with lived experiences of disability, characterised as a mana-enhancing descriptor emphasising empowerment and self-determination within the Māori context [58]. Together, these interpretations reflect a dynamic and evolving understanding of disability within the Māori community, rooted in the ongoing negotiation between traditional values, contemporary challenges, and the pursuit of holistic well-being.

2.4.3 Māori Perspective in Rehabilitation

In the thesis titled "Mana Motuhake Ringa: The Non-Invasive Neural Interface Based Artificial Hand," Owen extensively draws upon mātauranga Māori concepts as a guiding framework for the development of an upper limb prosthesis [59]. This endeavour uniquely merges an innovative autonomous hand framework with mātauranga Māori, resulting in an unprecedented approach to restoring hand function. Notably, this work places a significant emphasis on mauri, which represents the life force and intrinsic essence within all living entities. Moreover, the study reinforces the Wairua theory as proposed by Elder and Kersten in 2015 [50]. This theory recognises that alongside physical injuries, there exists a spiritual injury that accompanies them.

In Owen's research, the stages of neural interface design are framed as distinct phases of Raranga, the Māori art of weaving. This analogy provides a captivating lens through which to perceive the design process. Each phase and the correlating processes are outlined in table 2. This unique integration of Māori cultural concepts and cutting-edge technological practices offers a holistic and innovative framework for the advancement of neural interface design [59].

Table 2: Stages in the process of raranga

Phase	**Process**	**Neural Interface Design**
Hauhake	Harvesting of materials	Acquisition of physiological signals from the body
Whakarite	Preparation of materials before crafting	Pre-processing of signals
Raranga	Manipulation of the material in accordance with the established design	Application of machine learning algorithms and the process of pattern recognition

In the context of disability-related literature, Smiler also incorporates insights from raranga (weaving) to shape the methodology, exploring the effects of early intervention on Māori deaf children and their whānau [60]. Drawing a parallel with the process of selecting harakeke (flax) for weaving, the author likens the choice of cases for assessment to the careful selection of harakeke rau (leaves) for preparing the whenu (foundation). Mirroring the practices of weavers who keenly observe environments where harakeke plants with specific qualities thrive, information about potential cases for assessment is

exchanged within networks. This research adopts a similar approach by sourcing relevant material through a discerning exploration of environments and collaborative information exchange. Figure 10 depicts the process of raranga.

Figure 10: The process of raranga[60]

While the field of assistive technology design is only beginning to embrace mātauranga Māori perspectives within research, other domains such as health and social sciences have already made significant strides in this direction, serving as trailblazers for cross-disciplinary research. In the article titled "Gods, whānau, body parts – making sense of health with whakapapa," Te Miri Rangi refers to the pūrākau of Hineahuone, highlighting a fundamental perspective within mātauranga Māori in the context of health [61, 62]. The use of this pūrākau shows how whakapapa holds the power to introduce an additional layer of depth to our comprehension of the world. The understanding of these genealogies and interconnected relationships within the natural world has the capacity to influence and shape our behaviors, leading to the enhancement of a person's well-being. In Sullivan's research, the utilization of the Hineahuone pūrākau serves as a conduit to explore the significance of the human body within indigenous knowledge systems [63]. The narrative of Hineahuone links humanity to the realm of the atua (gods). Sullivan intricately maps out the whakapapa of the body by tracing the contributions from various atua that culminated in the creation of Hineahuone. Sullivan's study serves as a powerful lens explaining the contribution of atua to the human form. By shedding light on this intrinsic connection,

the work further enriches understanding of the human body within the broader context of Māori cosmology.

In Māori worldview, te taha wairua holds profound significance, encompassing the interconnectedness of individuals with the environment and their relationship with te ao Māori [64]. This connection finds tangible expression in the cultural practices and perspectives of the Whanganui Iwi. A pivotal moment occurred in 2017 when the Whanganui River achieved global recognition as the first river to be acknowledged as a living being and granted personhood [65]. This transformative step reflects the Whanganui Iwi's deep spiritual connection to the river. The Whanganui River is displayed in figure 11.

Figure 11: Photograph of the Whanganui River[65]

Central to their understanding is a whakataukī that encapsulates the essence of this relationship:

“E rere kau mai te awa nui mai te kāhui maunga ki Tangaroa, ko au te awa, ko te awa ko au.”

"The river flows from the mountains to the sea, I am the river, the river is me."

This expression not only recognizes the river as a living entity but also underscores the reciprocal relationship between the health of the river and the well-being of the people. It emphasizes the crucial role of water and the inseparable connection to the environment in the context of health. In the broader context of mātauranga Māori, the teachings highlight water as the primary medicine. Acknowledging that water constitutes a significant part of both the world and the human body, Māori wisdom underscores the ancestral link through water. As water circulates, having touched the lips of our forebears, risen to the heavens, and fallen back to the earth, it fosters a profound connection between

the present generation and their ancestors. This perspective emphasises the vital role of water in sustaining not only physical health but also the spiritual and ancestral bonds integral to the Māori worldview[66, 67].

Insights derived from the pūrākau and whakapapa of Tangaroa provide another compelling avenue for investigation around the origin of the brain. A thought-provoking interpretation posited by Hanara introduces a novel framework, suggesting that Tangaroa encapsulates the essence of the brain[68]. This proposition not only invites a fresh lens through which to perceive this atua of the marine realm but also sparks inquiry into how indigenous narratives might provide insights into the intricate dynamics of cerebral function. Hanara refers to Tangaroa as "Kaitiaki o te Wairoro," which translates to "Keeper of the brain." Hanara contends that Tangaroa, as the atua of the marine realm, is intricately linked to the brain through the pure essence of waitā, symbolising saline water (found in the brain), and salt (present in the ocean). Furthermore, Tangaroa's association with the creation and introduction of whakairo (carving) into te ao Māori, alongside his grandson Ruatepupuke, has interesting implications for the way the brain is viewed. Whakairo (carving) has a strong connection to memory, being one method used to build a repository of cultural knowledge for Māori. In a similar way memory is a key function of the brain. This interpretation sheds new light on Tangaroa's multifaceted role, intertwining his dominion over the ocean with the intellectual and mnemonic aspects of human existence.

In the exploration of mātauranga Māori within various fields of academic study, a captivating narrative emerges that reflects the deep-rooted connection between indigenous knowledge and contemporary research. This intricate web of understanding becomes evident when examining the utilisation of Māori storytelling practices to enhance comprehension and design in different academic fields. The integration of mātauranga Māori and modern technological advancements offers a unique and holistic approach to addressing complex challenges. This growing acknowledgment of indigenous perspectives underscores the importance of collaborative engagement and cultural resonance in shaping innovative methodologies and transformative insights.

Chapter 3: Prosthesis Design

3.1 Introduction

The advent of 3D printing technology has heralded a new era in the field of prosthetic design, offering unprecedented opportunities for innovation in the development of upper limb prostheses. Central to this investigation is the project's overarching aim: to enhance the quality of life for individuals with upper limb amputations. Given the prohibitive costs associated with traditional electromechanical prosthetic hands, which can range between $25,000 and $75,000 USD, there exists a pressing need for more accessible alternatives[5]. Despite the promise of 3D printing technology in democratizing access to prosthetic solutions, many of the currently available 3D-printed prosthetic hands fall short in terms of performance, often proving more cumbersome than beneficial for the end-users. In response to these challenges, this chapter is dedicated to the exploration of low-cost yet highly functional prosthetic designs. By leveraging the potential of 3D printing technology, it seeks to bridge the gap between affordability and functionality, aiming to deliver prosthetic solutions that not only meet the financial constraints of users but also significantly improve their quality of life. Through this endeavour, this thesis contributes meaningfully to the ongoing discourse in prosthetic development, marking a step forward in the quest for accessible prosthetic solutions for upper limb amputees.

This chapter delves into the design and development of four pioneering low-cost 3D-printed upper limb prosthetic hands: “First”, “Tuarua”, “Dre”, and “Jerry”. It outlines the design processes employed, providing detailed descriptions of each prosthetic hand, thereby setting the stage for their subsequent evaluation. The evaluation process employs a suite of investigations—including an outlining of the DoF each hand possesses, a calculation of the RoM of each hand, and the performance of the Kapandji test. Through a comparative analysis, this chapter aims to highlight the strengths and weaknesses inherent in each design, offering critical insights into their functionality and overall performance.

3.2 Prosthetic Hand Development

In the development of the four distinct prosthetic hands within this study, the engineering design process served as the cornerstone of the methodology, emphasising rapid prototyping and a circular design philosophy to facilitate continuous improvement. Each prosthetic hand, while unified in their aim to provide a cost-effective solution for amputees, features unique design characteristics tailored to meet specific functional requirements. Central to the fabrication of the prosthetic hands was the use of additive manufacturing through fused deposition modelling (FDM) 3D printing, which allowed for the precise and cost-effective production of complex geometries. Each hand was printed using Polylactic Acid (PLA), a material selected for its balance of strength, durability, and availability. PLA's properties make it an ideal candidate for creating lightweight yet robust prosthetic limbs, catering to the functional

and aesthetic needs of the users. To ensure accessibility and maintain the cost-effectiveness of the prosthetic hands, the design incorporated locally available, off-the-shelf electronic components. This approach not only streamlined the assembly process but also facilitated easier repairs and upgrades, aligning with the principles of circular design. By utilising readily available components, the prostheses are more accessible with the repairs and maintenance being simplified. Figure 12 shows the Prusa MK3 3D printer used in this process.

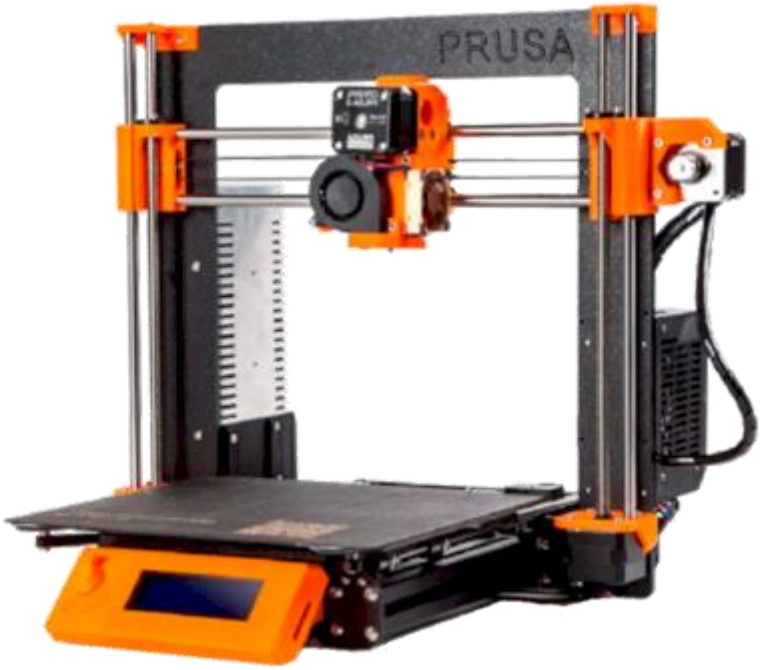

Figure 12: Prusa MK3 3d printer

Each prosthetic hand was modelled after the right hand, incorporating varying design characteristics to explore different aspects of functionality and user experience. Despite these variations, a unifying goal was to ensure that the total cost of production did not exceed $600. This cost constraint was critical in making the prosthetic hands more accessible to a wider population, addressing the significant financial barrier posed by traditional electromechanical prostheses. Through adherence to these design specifications and processes, the project aims to not only advance the state of prosthetic technology but also to democratize access to such essential devices, ultimately contributing to an improved quality of life for upper limb amputees.

This section will describe each of the four prosthetic hands developed as test beds for evaluation. The first part of this section will discuss the mechanical configurations and arrangements of the hands named “First”, “Tuarua”, “Dre” and “Jerry”. The section will then evaluate the hands through analysis of their DoF, their ranges of motion and their thumb dexterity, via the established Kapandji test.

3.2.1 Hand 1: “First”

The first design, referred to as the “First” Hand is shown in figure 13. This hand features a unique finger structure with each finger, comprising of trapezoidal segments that form non-rigid interconnections, aiding in the adaptive grasping of objects.

Figure 13: "First" Hand

A novel aspect of this design is the use of an elastic hair tie, which is threaded through two holes in the back of these segments and secured beneath the palm. This hair tie provides the necessary elastic tension for retracting the fingers back to their extended position. For finger flexion, the design integrates a nylon flexion tendon. This tendon attaches to the top of each finger and runs through the front of the trapezoidal segments, eventually connecting to a servo motor. Figure 14 shows the fingers in partial flexion.

Figure 14: Fingers of "First" hand in partial flexion

The thumb design features a metacarpal with a blocked hinge set at a 45-degree angle from the wrist as shown in figure 15. The thumb is actuated by a tendon that extends from the palm's front to insert into the metacarpal, with additional elastic tension applied between the block side of the metacarpal and the palm's inner surface. The thumb's MCP joint is designed to allow for abduction/adduction movements.

Figure 15: Thumb of "First" hand

Actuation of this prosthetic hand is achieved through the use of four servo motors, with three dedicated to the thumb's distinct movements and one for the flexion of the remaining fingers. The palm of this design is characterised by a block-like structure, contributing to a rigid wrist setup.

3.2.2 Hand 2: “Tuarua”

The “Tuarua” hand, shown in figure 16, presents an underactuated finger system with each finger possessing three DoF and driven by a dedicated servomotor.

Figure 16: "Tuarua" hand

The fingers incorporate pinned flexor revolute joints, enabling a motion range of up to 100 degrees. The design employs a flexion tendon crafted from monofilament nylon, strategically threaded through a slot located at the front of each phalanx. Figure 17 shows the fingers in partial flexion.

Figure 17: Fingers of "Tuarua" hand in partial flexion

Additionally, a carefully engineered pulley mechanism is integrated within the metacarpal. This mechanism plays a crucial role in minimizing friction along the flexion tendons, thereby enhancing the fluidity and efficiency of finger movements.

Furthermore, the design incorporates rubber extension tendons (Figure 18), intricately woven across the back of each finger joint. This weaving technique draws inspiration from traditional Māori art, specifically the tukutuku and taniko patterns. This choice not only pays homage to these cultural art forms but also functionally mimics the natural arrangement of the extensor hood's insertion points in a human hand, thereby mirroring the complex yet efficient biomechanics of human anatomy.

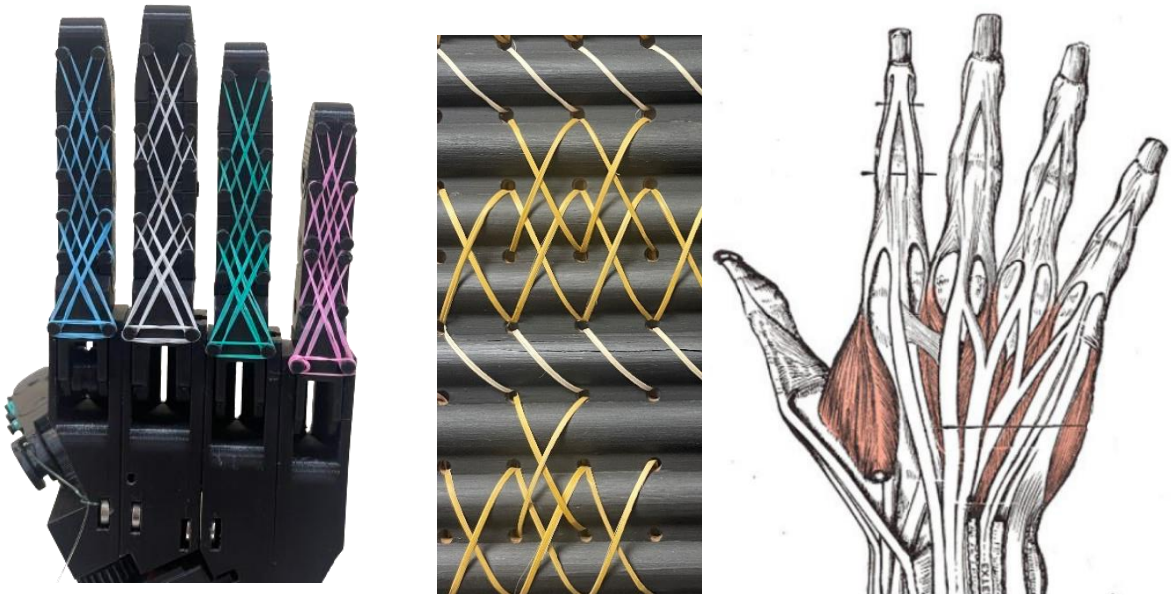

Figure 18: "Tuarua" hand extensor tendons compared to tukutuku panels and the extensor hood of anatomical fingers

The thumb in the Tuarua design is underactuated as well, offering 4 DoF. Its complex movement is enabled by an offset geared servo mounted at a 45-degree angle to the palm, driving a spur gear attached at the thumb's carpometacarpal (CMC) joint. Additionally, the thumb features a 180-degree revolute joint at the metacarpal's base for abduction/adduction movements.

The palm of the Tuarua hand is notable for its modular design, featuring sliding metacarpals held in place with neodymium magnets. This allows for easy removal and customisation of fingers. The forearm of this design houses six servo motors within a cylindrical base and a stacked, tower-like structure. However, it lacks forearm covers, potentially exposing the internal structures and components to external forces and elements.

3.2.3 Hand 3: “Dre”

The third design is the “Dre” hand as depicted in figure 19.

Figure 19: "Dre" hand

The Dre Hand adopts a different approach by designing fingers with two DoF, specifically at the MCP and PIP joints. The hand's distinct feature is the fusion of the distal and intermediate phalanx into a rigid member, coupled with a bar linkage that drives both flexion and extension motions. Figure 20 shows the fingers in partial flexion.

Figure 20: Fingers of "Dre" hand in partial flexion

The thumb of the Dre Hand, shown in figure 21, is designed with 3 DoF and features a tendon mechanism for flexion and extension. A bar linkage, attached to the base of the thumb's metacarpal and actuated by a servo motor at the palm's base, allows for a wide range of thumb movements, including opposition and reposition.

Figure 21: Thumb of "Dre" hand

The palm is constructed in three pieces: a central plate for mounting fingers and servos, a front plate with a cut-out for the thumb opposition linkage, and a back plate that screws securely into the backside. The wrist of the Dre Hand is based on a bar linkage system, capable of 90 degrees of motion in flexion/extension and powered by a larger servo motor for enhanced control. The forearm is designed as a two-piece construction, housing the wrist servo motor and securely attaching to the middle palm mount through hinge joints, providing a robust and enclosed structure.

3.2.4 Hand 4: “Jerry”

The “Jerry” hand, shown in figure 22, features a similar level of innovation in prosthetic hand design.

Figure 22: "Jerry" hand

Its fingers have two DoF, with a notable incorporation of a fixed DIP joint and a torsion spring mechanism for joint extension. Stability and controlled movement in the fingers are ensured using pinned revolute joints, secured with 2mm steel pins. The flexion of the fingers is driven by a 20lb fishing braid, and the fingers themselves are designed as elliptical cylinders with 35-degree chamfers to facilitate clearance during flexion. Figure 23 shows the fingers in partial flexion.

Figure 23: Fingers of "Jerry" hand in partial flexion

The thumb in the Jerry design mirrors that of the Dre Hand, featuring the same design elements and functionalities to promote consistency in hand movements. Figure 24 depicts the thumb of the “Jerry” hand.

Figure 24: Thumb of "Jerry" hand

The wrist remains rigid in this design, providing stability during operation and minimising unnecessary complex movement. The palm construction is identical to that of the Dre Hand, with a three-piece assembly that includes a central plate for mounting fingers and servos, a front plate with a thumb opposition linkage cut-out, and a back plate that screws securely into the backside. The design of the MCP joint allows for a strong interference fit, ensuring the structural integrity of the hand.

3.3 Evaluation Methods

The evaluation of prosthetic hands involves a series of tests designed to assess their functionality and performance. Three tests were selected; the Degrees of Freedom, the Range of Motion analysis and the Kapandji test. This section explains each test including its purpose, describes the test procedure, details the data collection method and presents the initial results of each evaluation method.

3.3.1 Degrees of Freedom Analysis

The Degrees of Freedom (DoF) analysis assesses the mechanical capabilities of prosthetic hands, measuring the number of independent movements each hand can perform. This analysis is crucial for understanding how effectively a prosthetic can simulate the complex movements of a natural hand. The motion of joints of an anatomical human hand can be described by the DF within the joint. Figure 25 depicts a simplified diagram of the DoF of each joint of a natural human hand. Of the fingers, the DIP and PIP joints are limited to one DoF; flexion-extension. The MCP joints allow for 2 DoF; flexion-extension and ulnar/radial deviation. The CMC joint locate between the first metacarpal of the thumb and the trapezium carpal bone allows for 3 DoF; flexion-extension, abduction-adduction and axial rotation.

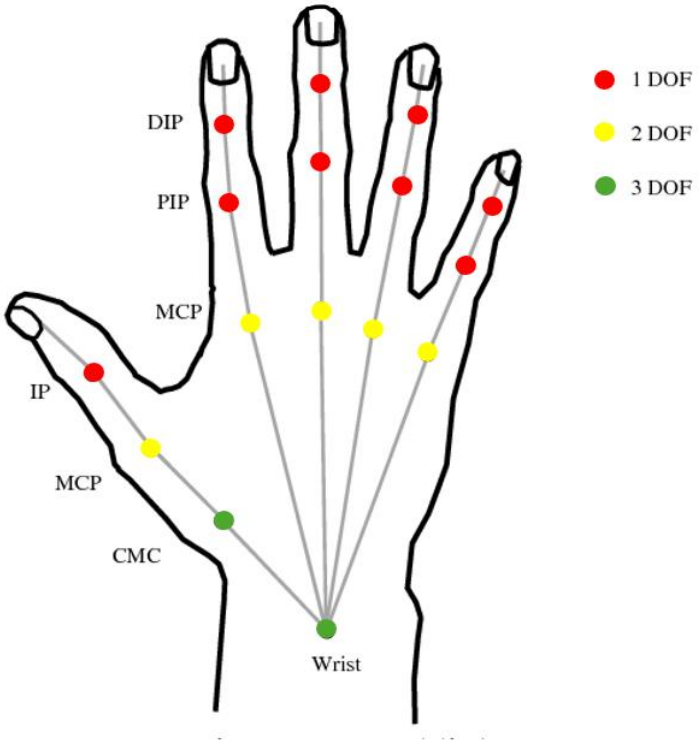

Figure 25: Degrees of freedom of the human hand

The test involves systematically moving each joint in the prosthetic hand to document the types of movements it can perform, including flexion, extension, abduction, and adduction. Each movement's

range is measured to determine the prosthetic's mechanical flexibility and capability. The movements and their range are recorded for each finger and the thumb, with the total DoF calculated for the entire hand. The data will be presented in a tabulated format, listing the DoF for each joint and the RoM observed. Comparative analysis across the prosthetic designs will highlight their mechanical sophistication and potential functional versatility.

The findings are organised as bar graphs with each bar representing the DoF of each specific finger, to provide a clear comparison between the prosthetic hands and the natural human hand in terms of DoF. Figure 26 shows the DoF of each finger within the hand and figure 27 shows the total DoF of each hand.

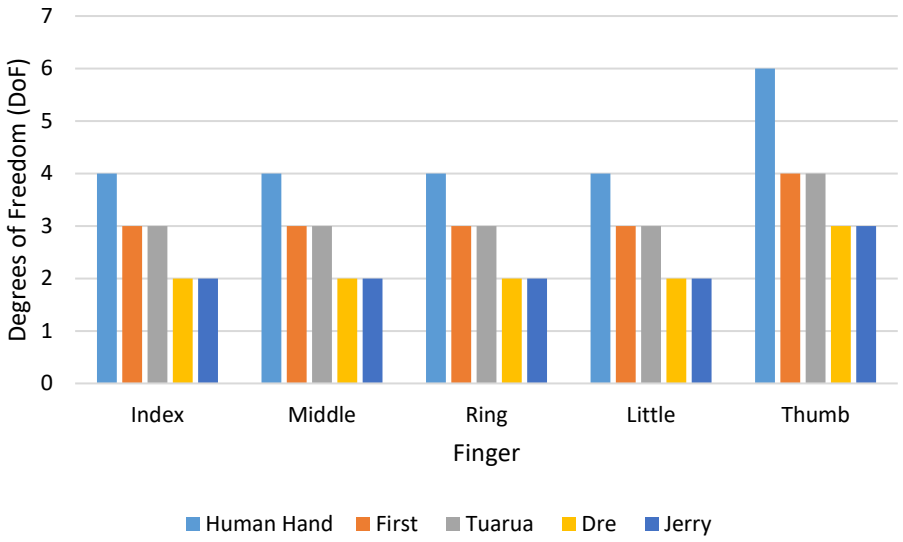

Figure 26: Degrees of freedom for each digit of the designed hands.

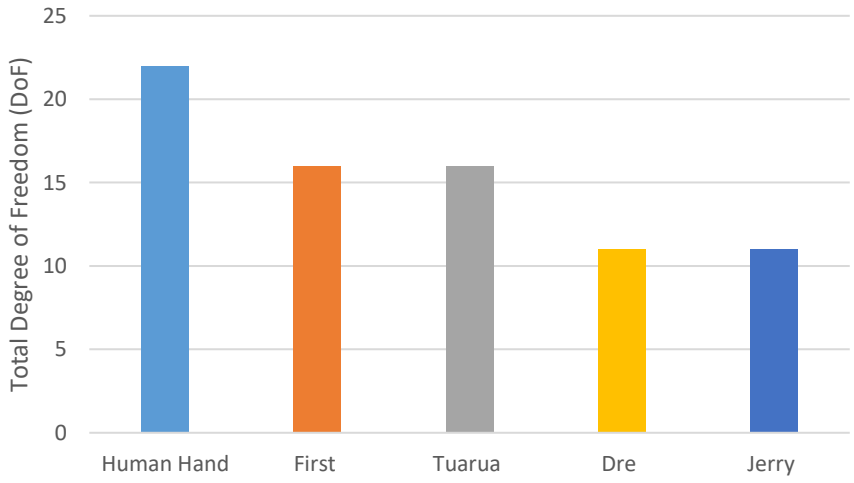

Figure 27: Total degrees of freedom of the designed hands

3.3.2 Finger Range of Motion (RoM) Analysis

The analysis of prosthetic fingers' RoM through the DH Convention provides a detailed understanding of their mechanical capabilities. The anatomical human finger has 3 phalanges: the proximal, the intermediate and the distal which can be represented as a three-link chain actuated through revolute joints. This section discusses the application of the DH Convention to a three-link chain for determining the maximum RoM of prosthetic fingers. Due to the thumb's complex anatomy and movement patterns, which are not fully defined by revolute joints alone, it will not be evaluated using the DH Convention in this analysis. The thumbs evaluation is taken care of in the next section through the Kapandji test. The DH Convention facilitates the representation of joint and link configurations within robotic systems. This standardised approach simplifies the mathematical modelling, providing a framework for analysing the kinematics of each finger segment. The model incorporates three links l_1, l_2, l_3 and three joint angles $\propto_1, \propto_2, \propto_3$. These parameters describe the lengths of the finger segments and the angles between them, essential for constructing the transformation matrices[69]. Figure 28 shows a diagram of the kinematic structure of a finger described by the DH convention.

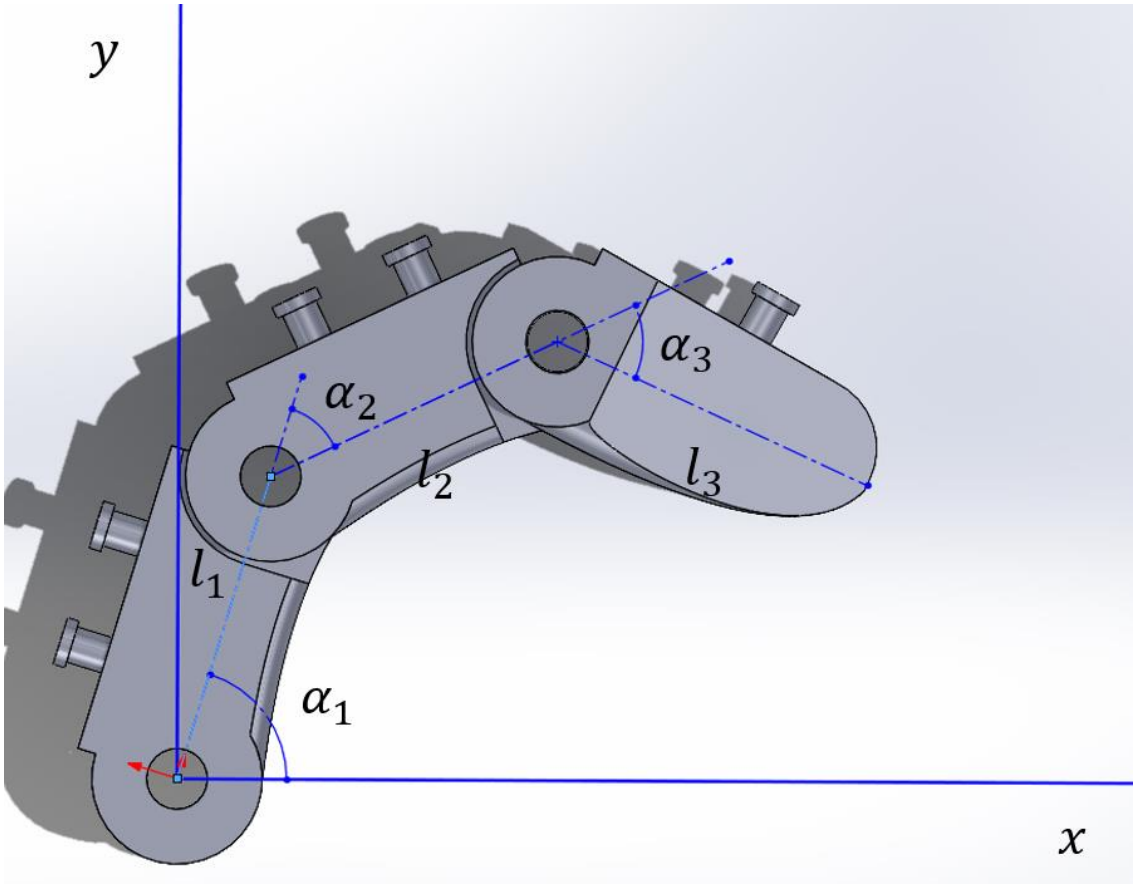

Figure 28: Kinematic structure of a finger

The kinematic analysis of a three-link chain involves deriving transformation matrices for each link, based on their DH parameters. These matrices describe the position and orientation of each link relative to the previous one.

For each link in the three-link chain, a transformation matrix is defined as follows:

$$T_n = \begin{bmatrix} cos \propto_n & -sin \propto_n & 0 & l_n cos \propto_n \\ sin \propto_n & cos \propto_n & 0 & l_n sin \propto_n \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The complete spatial transformation from the base to the finger's tip (end effector) is given by the product of these matrices:

$$H = T_1 \cdot T_2 \cdot T_3$$

This matrix *H* encapsulates the cumulative positional and orientational changes across the three links, providing a comprehensive model of the finger's movement.

By varying the joint angles $\propto_1, \propto_2, \propto_3$ within their physiological limits (0 to 90 degrees), the analysis simulates the complete range of finger movements. This process establishes the boundaries of how the prosthetic finger can flex and extend, replicating natural hand functions.

The position of the end effector is determined for each set of joint angles, illustrating the finger's maximum RoM. The coordinates (x, y) of the tip are calculated, allowing for the plotting of each finger's movement trajectory:

$$x = l_1 cos \propto_1 + l_2 cos(\propto_1 + \propto_2) + l_3 cos(\propto_1 + \propto_2 + \propto_3)$$

$$y = l_1 sin \propto_1 + l_2 sin(\propto_1 + \propto_2) + l_3 sin(\propto_1 + \propto_2 + \propto_3)$$

The maximum trajectory of each finger, derived from the DH analysis, will be plotted in two dimensions. This provides a visual representation of the extent and pattern of movement each finger can achieve. To offer a comprehensive view of the fingers' RoM in a spatial context, the trajectories of all fingers on each prosthetic hand will be plotted in 3D. This visualisation captures the combined movements of the fingers, illustrating how they work together to perform grasping and other hand functions.

This section provides a thorough examination of the kinematic properties of prosthetic fingers, leveraging precise measurements and computational analyses to understand their functional capabilities. The results are structured to include references to essential figures and tables that elucidate the RoM and spatial arrangement of the fingers for each prosthetic hand.

The foundational data for the kinematic analysis are detailed in appendix 3.1 which presents the measurements of each phalanx l_1, l_2, l_3 and the overall dimensions of each finger across the examined prosthetic hands.

Using MATLAB, a comprehensive kinematic analysis was conducted to determine the RoM for the prosthetic fingers. This involved calculating the x and y positions for all joint angle combinations and employing the boundary function to visualise the movement limits. The 2D planar analysis offers a clear visualisation of the operational boundaries for each finger, showcasing the extent of achievable movements. The spatial arrangement of the fingers is critical for understanding the hand's overall functionality. Appendix 3.2 provides data on the positioning of each finger relative to the other fingers. The z co-ordinates specified represent the location of the MCP join along the palm at $y = 0$ on the $y - z$ axis, with the origin $(0,0)$ designated as the MCP of the little finger.

The 3D spatial representations extend the analysis by combining individual finger movements into a cohesive model of each hand's operational capability. The 3D RoM for the First Hand is visualised, showcasing how the fingers work together to perform complex tasks in figure 29. The 2D finger RoM for the First Hand is illustrated in figure 30, highlighting the kinematic flexibility of each finger.

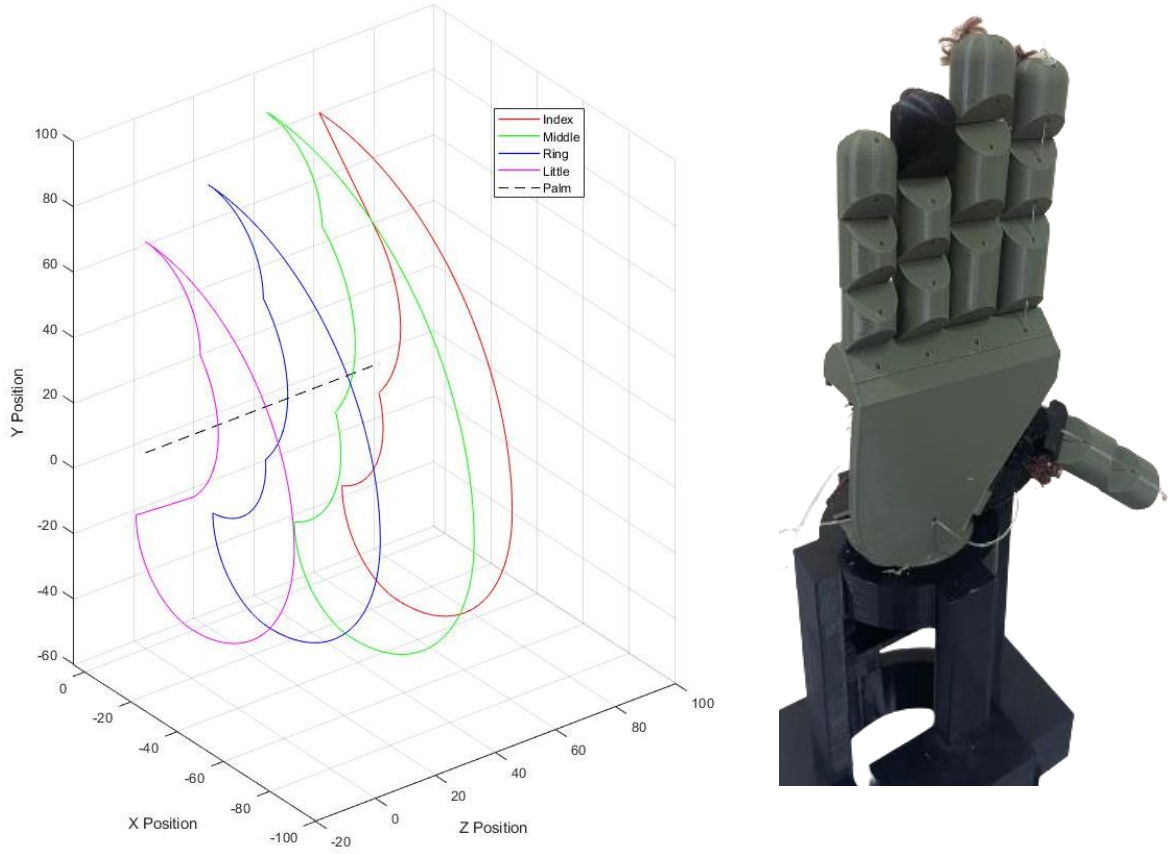

Figure 29: 3D range of motion plot for "First" hand

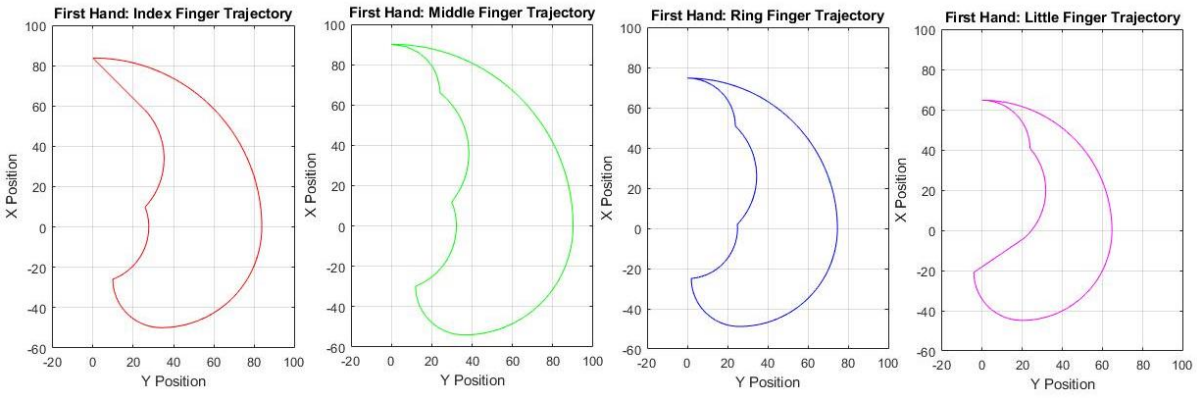

Figure 30: 2D range of motion for "First" hand fingers

The Tuarua's 3D RoM, shown in figure 31, illustrates the integrated movements of its fingers, highlighting the prosthetic's potential for dexterity. Similarly, the 2D RoM for Tuarua's fingers is depicted in figure 32, demonstrating the hand's unique kinematic capabilities.

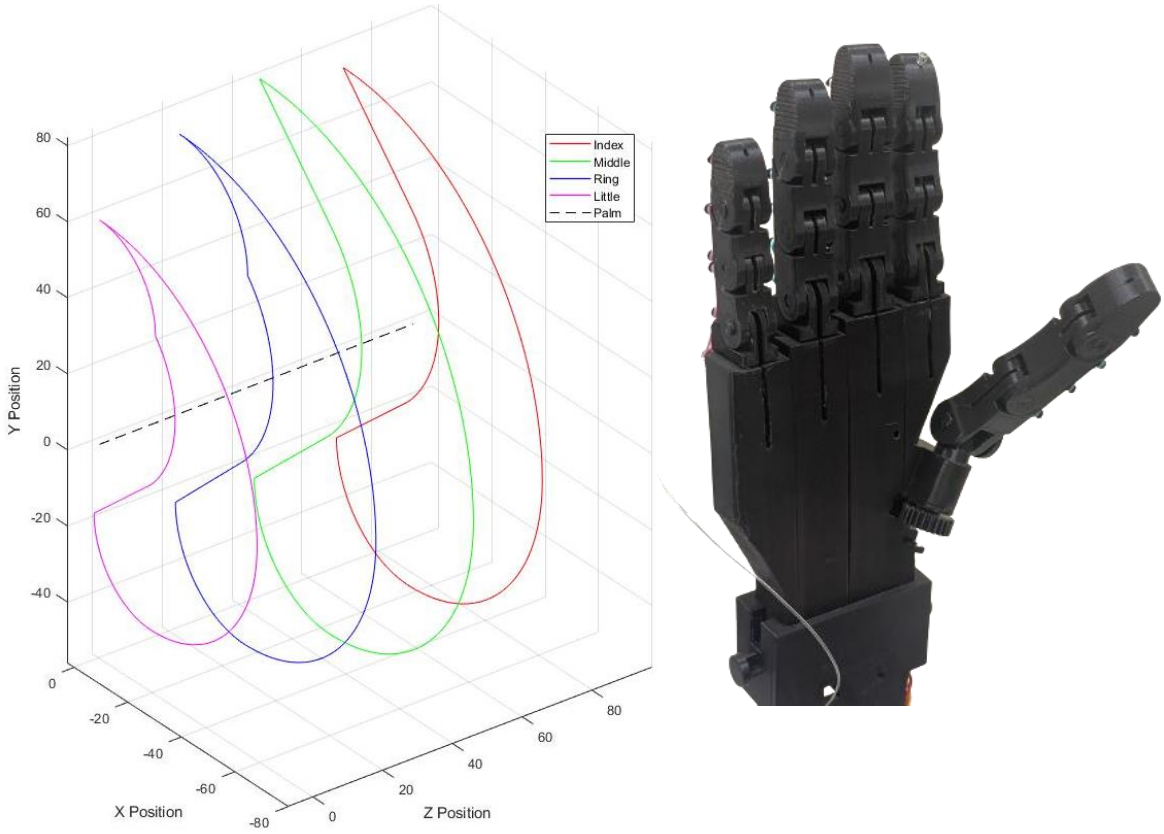

Figure 31: 3D range of motion plot for "Tuarua" hand

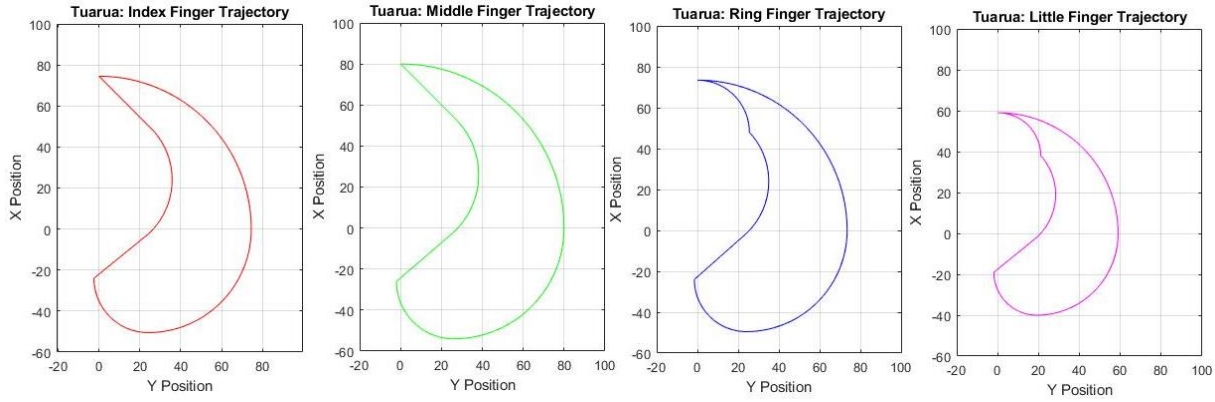

Figure 32: 2D range of motion plot for "Tuarua" hand fingers

Figure 33 depicts the 3D RoM for the Dre Hand is depicted, revealing the synergistic finger movements that contribute to its functionality. The 2D finger RoM plots are included below in figure 34.

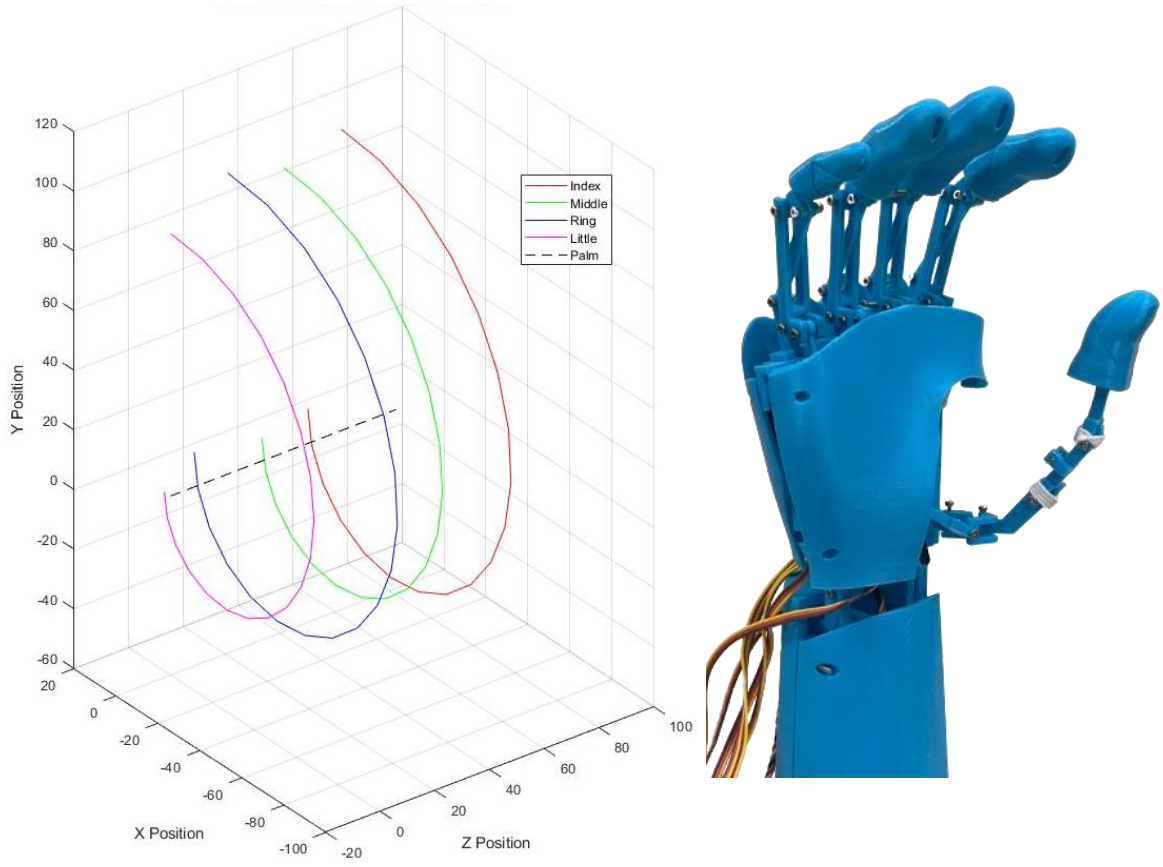

Figure 33: 3D range of motion plot for "Dre" hand

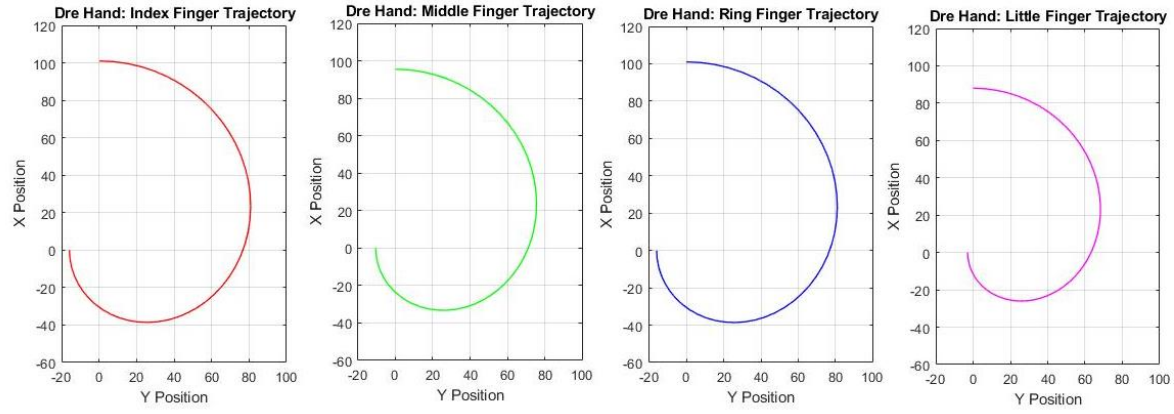

Figure 34: 2D range of motion plot for "Dre" fingers

Finally, the Jerry Hand's 3D RoM is shown in figure 35, offering a perspective on the hand's kinematic efficiency and the interplay between finger movements. The Jerry Hand's 2D RoM is presented in figure 36, providing insights into the operational range of its fingers.

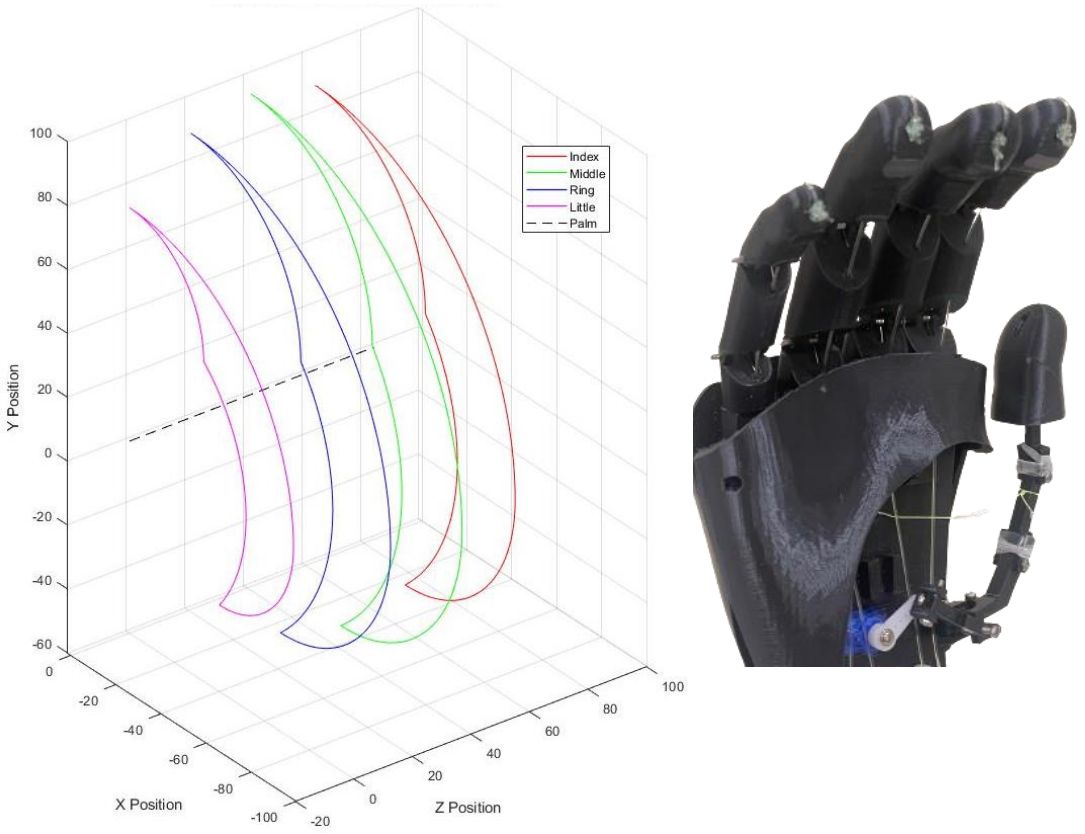

Figure 35: 3D range of motion plot for "Jerry" hand

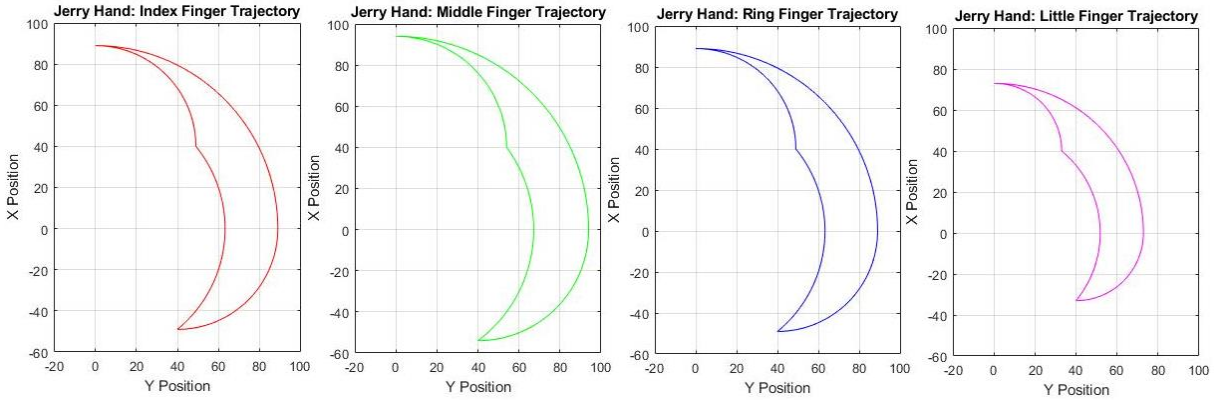

Figure 36: 2D range of motion plot for "Jerry" hand fingers

3.3.3 The Kapandji Test

The Kapandji test measures the dexterity and functional range of the thumb, which is pivotal in grasping and object manipulation. This test aims to evaluate the prosthetic thumb's practical usability by assessing its ability to perform essential movements.

The test scores the thumb's ability to touch various points on the hand, from the base of the little finger to the distal crease of the palm. Each successful contact is scored, with the total score ranging from 0 to 10, where higher scores indicate greater thumb dexterity and functional range[70]. Table 3 denotes the location of each evaluation position.

Table 3: Numbering system of the Kapandji Test

Position Number	Location
1	Radial side of the proximal phalanx of the index finger
2	Radial side of the intermediate phalanx of the index finger
3	Tip of the distal phalanx of the index finger
4	Tip of the distal phalanx of the middle finger
5	Tip of the distal phalanx of the ring finger
6	Tip of the distal phalanx of the little finger
7	DIP joint crease of the little finger
8	PIP joint crease of the little finger
9	MCP joint crease of the little finger
10	Distal palmar crease

The scores are documented for each prosthetic hand's thumb, providing a quantitative measure of its functional range and dexterity.

This section presents the results of the Kapandji test performed on each prosthetic hand model, focusing on their ability to replicate the thumb's pivotal movements in grasping and object manipulation. The test's outcomes are summarized in Table 4, providing a comparative view of each hand's performance based on their Kapandji scores, which range from 0 to 10, with higher scores indicating greater thumb dexterity and functional range.

Table 4: Results of the Kapandji Test

	1	2	3	4	5	6	7	8	9	10	Total
First Hand	Y	Y	Y	Y	Y	N	N	N	N	N	5
Tuarua	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	10
Dre Hand	Y	Y	Y	Y	N	N	N	N	N	N	4
Jerry Hand	Y	Y	Y	Y	N	N	N	N	N	N	4

By structuring the evaluation methodology in this manner, the research aims to provide a comprehensive and systematic assessment of each prosthetic hand's design and functionality. This approach not only quantifies the prosthetic hands' capabilities but also offers valuable insights for future design improvements, ensuring that the prosthetics meet the end-users' needs effectively.

3.4 Discussion

The exploration of four distinct 3D-printed prosthetic hands has provided significant insights into the challenges and opportunities in designing prosthetics that closely mimic the functionality of the human hand. This discussion delves deeper into the findings from the DoF analysis, the Range of Motion (RoM) tests, and the Kapandji evaluation, generating new talking points on the implications of these results for future prosthetic hand design and development.

3.4.1 Degrees of Freedom

The human hand's 22 DoF sets a high benchmark for prosthetic designs. The “First” Hand and “Tuarua” hands achievement of 16 DoF represents a significant stride toward this goal. However, the concept of underactuation, despite its benefits for adaptive grasping and conforming grip, introduces complexities in achieving a balance between mechanical simplicity and functional versatility. Underactuation facilitates a more natural interaction with objects by allowing the fingers to conform to their shape. This feature is particularly beneficial in prosthetic hands, as it enables users to handle a variety of objects with ease, enhancing the prosthetic's utility in everyday tasks. While the “First” Hand's approach to using only four actuators to actuate 12 DoF aims to simplify the design and reduce costs, it also limits the hand's ability to perform precise and controlled movements. The suggestion to implement a tendon differential mechanism could address some of these limitations by distributing the actuation force more evenly across the fingers, potentially improving the hand's dexterity without significantly increasing its complexity.

The thumb's unique functionality in the human hand—owing to its opposition and wide RoM—poses specific challenges for prosthetic designs. “Dre” and “Jerry” lack full flexion/extension in the thumb, which underscores the difficulty in replicating the thumb's versatile movements. The absence of full flexion/extension in the thumb could compromise the effectiveness of power grasps, limiting the user's ability to perform tasks that require significant force or stability. This limitation highlights the need for innovative design solutions that enhance the thumb's articulation in prosthetic hands.

3.4.2 Effects of RoM

By examining the RoM across various designs, particularly focusing on the distinction between fingers with three joints versus those with two, and considering the implications of finger length and coupling mechanisms, we can derive several key observations and recommendations for future prosthetic hand design.

Fingers equipped with three joints inherently exhibit a greater RoM, closely mimicking the natural articulation of human fingers. This design is crucial for executing a broad spectrum of tasks, from precise manipulations to robust grasps. Tuarua's design, with longer fingers, showcases the potential

for achieving an extensive RoM, thereby enhancing the hand's dexterity and versatility. An interesting observation from the RoM analysis is the impact of the length ratio between the distal and proximal phalanges on the achievable motion. When the distal phalanx is longer, the RoM is inadvertently constrained by the palm, limiting the ability to achieve 90 degrees of flexion simultaneously at all joints. This limitation suggests a design recommendation for prosthetic fingers: designing the proximal phalanx to be longer than the distal can mitigate this issue, enabling more effective palm contact and grasp formation. Design Consideration for Two-DoF Fingers: For fingers designed with only two DoF, it becomes imperative to allow for rotation beyond 90 degrees to facilitate effective palm contact. This consideration is crucial for ensuring that the prosthetic hand can perform a wide range of grasping actions, from pinching to encompassing larger objects.

The “Dre” Hand's design employs a coupled system, where the movement of the end effector follows a predefined path due to the mechanical linkage between joints. This setup offers notable benefits, including reliability and repeatability in the movement path, leading to more precise grasping actions. However, the fixed nature of this path also introduces limitations in adaptability, as the fingers cannot conform as readily to the contours of grasped objects. In contrast, prosthetic hands utilising tendon-driven systems offer a broader area within which the end effector can move, providing a more adaptable grip that can conform to various object shapes. While this design enhances the prosthetic's versatility in handling diverse objects, it may also introduce variability in the finger positioning, potentially affecting the precision and predictability of grasps.

3.4.3 Functional Dexterity

Tuarua's perfect Kapandji score is indicative of its design's potential for high functional dexterity, which is crucial for a wide range of grasping and manipulative tasks. This achievement highlights two key aspects: the importance of thumb design and adaptive grasping. The thumb's unique RoM and opposition capability are critical for effective hand function. Tuarua's design success in this area suggests that focusing on the thumb's articulation can significantly enhance overall prosthetic functionality. Future designs might benefit from prioritising thumb mobility and control to improve task performance. The high score achieved by Tuarua underscores the potential advantages of adaptive grasping mechanisms. These mechanisms, facilitated by underactuated designs, allow the prosthetic to adjust to the shape and size of various objects, providing a more natural and efficient grip. This adaptability is especially beneficial for performing daily activities that require fine motor skills and manipulation.

3.4.4 Design Considerations and Real-World Applications

The real-world application of prosthetic hands like “Tuarua” and the “First” hand has underscored several critical design considerations that must be addressed to enhance their functionality, reliability,

and safety. These considerations not only impact the user experience but also influence the overall effectiveness of the prosthetic in daily use. “Tuarua” and “First” both utilise elastic bands in their design, which, while cost-effective and easily replaceable, present issues in terms of durability and consistency. The propensity of these bands to snap or lose elasticity over time necessitates frequent replacements, adding to the maintenance burden for users. This variability in elasticity can lead to unpredictable performance, affecting the prosthetic's reliability. In contrast, the use of springs in the Jerry Hand represents a more durable solution, offering consistent tension and longevity. This approach reduces the need for frequent maintenance and ensures more stable performance over time.

The presence of exposed gears, particularly in designs like Tuarua, poses significant health and safety risks. These risks include pinch points that can injure the user and the potential for external objects to become entangled, causing damage to the prosthetic. Addressing these risks requires thoughtful design adjustments to shield or encase vulnerable components.

3.5 Future Directions and Considerations

Building upon the lessons learned from the evaluation of these prosthetic hands, future design efforts can explore innovative solutions that address the identified challenges while leveraging the strengths of each approach. A promising direction is the development of a hybrid actuation system that combines the precision of coupled mechanisms with the adaptability of tendon-driven systems. For example, driving the MCP joint with a coupled actuator and the PIP & DIP joints with tendons could offer an optimal balance. This configuration allows for precise positioning of the finger while retaining the ability to adaptively grasp objects of various shapes and sizes. Future designs should prioritize the use of materials that combine durability with flexibility. Advanced polymers, composite materials, or even innovative uses of traditional materials like springs could provide the necessary performance without the drawbacks of current systems.

3.6 Conclusion

This chapter has presented the development and evaluation of four prosthetic hands: "First," "Tuarua," "Dre," and "Jerry." These hands were assessed through a series of tests focusing on Degrees of Freedom (DoF), Range of Motion (RoM), and the Kapandji score, providing valuable insights into the mechanics of prosthetic hand functionality and their potential impact on user experience. The findings reveal that prosthetics with higher DoF, particularly those utilising underactuated tendon systems, excel in adaptive grasping, offering significant benefits in terms of RoM. However, the predictability of the end-effector's path remains challenging with these systems.

This opens the door to exploring hybrid systems that merge the benefits of underactuated and coupled systems. A hybrid approach promises to offer the best of both worlds: the adaptability and flexibility of underactuated systems combined with the precision and predictability of coupled mechanisms. Such systems could provide upper limb amputees with a prosthetic solution that enhances their ability to interact with their environment and offers greater control and reliability in the positioning of the end effector.

This research aligns with advanced prosthetic technology to improve the quality of life for upper limb amputees. By exploring innovative design solutions, such as hybrid systems, we move closer to creating prosthetics that offer functionality and user control, embodying a significant step forward in prosthetic development. As a result, the aim of this work to increase the quality of life for amputees by improving the rate of prosthetic acceptance is achieved, to some degree, through the mechanical improvement of function and dexterity in upper limb prosthetic devices. Another significant reason for prosthetic rejection is the way prosthetics are controlled, the following chapter adds upon this chapter by addressing the challenges associated with upper limb prosthetic device control.

Chapter 4: Control Systems

4.1 Introduction

EMG has long been the cornerstone of prosthetic control, allowing amputees to manipulate their prosthetic limbs through the electrical activity generated by muscle contractions. This technology has facilitated significant advancements in prosthetic functionality, enabling users to perform a wide range of tasks with increased autonomy. However, EMG-based systems have limitations, particularly for individuals facing complex neuromuscular conditions or those with limited residual muscle activity, where EMG signals may be weak or difficult to discern.

In search of alternatives that can accommodate a broader spectrum of users, EEG emerges as a promising solution. By directly tapping into the brain's electrical activity, EEG offers a novel approach to prosthetic control, potentially providing a more intuitive and inclusive operation for a wider range of amputees.

This section delves into constructing an EEG control system tailored for prosthetic use, focusing on two primary training methodologies: Motor Execution and Action Observation, the latter facilitated by the use of a digital twin. This digital twin simulates the grasps of the “Jerry” hand through the EEG control system. Through these training regimes, users are equipped with the skills needed to command their prosthetics using neural signals alone. The efficacy of these approaches is assessed in a series of tests, evaluating both single grasp and multi-grasp capabilities to determine their potential to enhance prosthetic functionality and user experience.

By venturing into the realm of EEG-controlled prosthetics, this research aims to broaden the horizons of prosthetic technology, offering new avenues for individuals to regain independence and improve their quality of life, irrespective of their specific physical challenges.

4.2 EEG Control System Architecture

This section outlines the system architecture of an EEG-controlled prosthetic hand, detailing the flow from data acquisition through the Emotiv Insight to the final command output that actuates the prosthesis. The architecture integrates neurotechnology with sophisticated software and hardware components to translate brain activity into tangible actions. The section firstly looks at the handling of the data through data acquisition, pre-processing and feature extraction. It then delves into signal classification and grasp execution.

4.2.1 Data Handling and Classification

The system is based on the Emotiv Insight neural headset, a non-invasive EEG device designed for EEG data acquisition. This commercially available, 5-channel wireless headset employs semi-dry polymer sensors, adhering to the International 10-20 sensor configuration for optimal brainwave detection, as shown in Figure 37 [71]. Additionally, it is equipped with 9-axis motion sensors to monitor head movements, ensuring accurate signal capture by distinguishing between neural signals and physical movements.

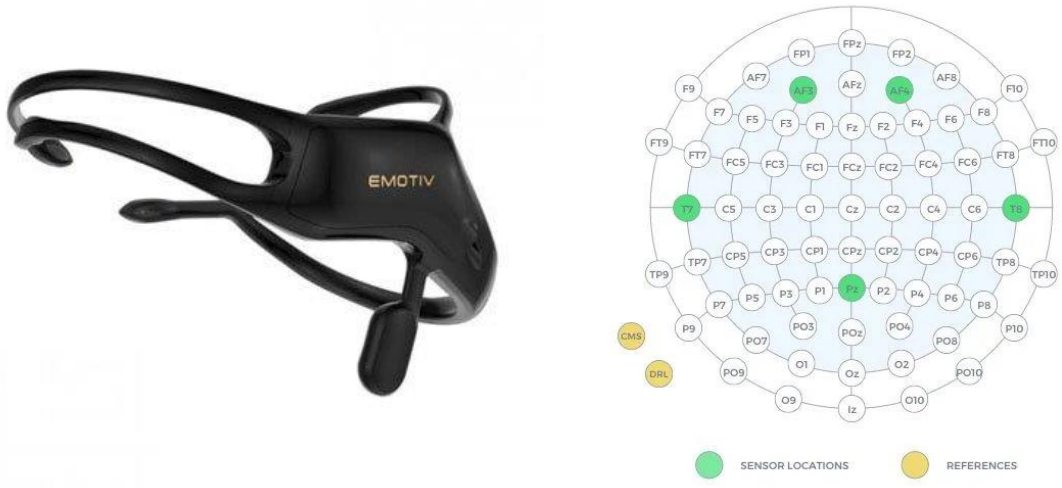

Figure 37: The Emotiv Insight sensor positions according to the International 10-20 sensor configuration[71]

Data is captured from the Emotiv Insight and streamed to Emotiv BCI-OSC, the flagship software for brain-computer interfacing provided by Emotiv. This software is pivotal for real-time data streaming and plays an important role in developing unique user profiles. It allows for monitoring cognitive performance metrics and interpretating mental commands, serving as the intermediary between raw EEG data and actionable inputs for the prosthetic system. Feature extraction is managed within the Emotiv BCI-OSC software environment, where significant patterns and characteristics within the EEG

signals are identified and isolated. These features are essential for the subsequent machine learning classification, as they represent the distinct neural signatures associated with different mental commands. Utilising Support Vector Machine (SVM) algorithms, the system classifies the extracted features into predefined mental commands. This machine-learning process is key to translating complex brain activity into understandable commands that the prosthetic system can execute. The SVM classifier is trained to recognise the user's intent based on the unique patterns present in their EEG data, allowing for a personalised and intuitive control experience[72]. The classified mental commands are then translated into specific actions via the Arduino IDE, which receives signals from the Emotiv BCI-OSC software. Each mental command is coded to trigger a corresponding function in the prosthetic hand. For instance, when the system receives a command with a strength greater than 0.5, indicating a deliberate action, the prosthetic is activated to perform one of the selected grasps. The system framework is outlined in Figure 38.

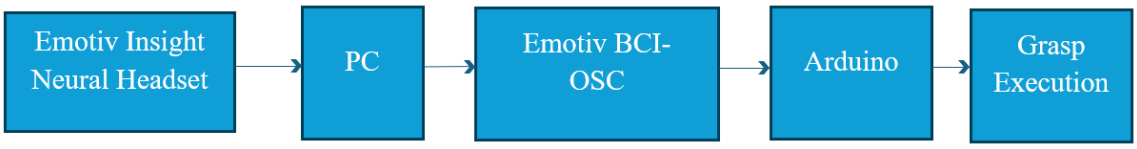

Figure 38: EEG prosthesis control system framework

4.2.2 Grasp Execution

The signals generated and handled through the Emotiv software are sent to the Arduino Uno microcontroller through the Arduino IDE as keystrokes. The Uno drives the servo motors to predefined positions that control the fingers of the prosthetic hand. This ensures that the prosthetic hand capabilities are robustly translated to respond to the output received from the EEG signal generated by the user.

As discussed in the previous chapter, four prosthetic hands were designed as potential testbeds for the control system. For this particular control system, “Jerry” was chosen. The "Jerry" hand was selected based on its notable reliability and capability to accurately replicate a variety of hand grasps. Four key grasps that are integral to accomplishing everyday tasks were identified by leveraging the GRASP taxonomy[18]. The selected grasps include the fist/power grasp, the palmar pinch, the lateral pinch and the tripod grasp. These grasps are defined earlier in chapter 2 and thegrasp qualities are further described below.

Fist/Power Grasp

The fist or power grasp (figure 39) is identified for its ability to accommodate objects of varying diameters, utilising a power grip. Serving as a cornerstone for manipulating items, the fist or power grasp enables the handling of objects ranging in size from large tools, such as hammers, to smaller everyday items, like toothbrushes, underscoring its fundamental role in daily activities.

Figure 39: "Jerry" hand in fist/power grasp

Palmar Pinch

Distinguished by its precision, the palmar pinch (Figure 40) uses pad opposition, focusing on the index finger and the thumb, both away from the palm. This grasp is pivotal for activities that require fine motor precision—picking up minute items like coins or precise instruments, exemplifying its necessity for detailed tasks.

Figure 40: "Jerry" hand in palmar pinch grasp

Lateral Pinch

Positioned within the intermediate grasp category, the lateral pinch (Figure 41) is characterised by side opposition. It utilises the index finger as the primary finger, with the thumb drawn towards the palm. This grasp is ideal for securing flat, slender objects like keys, cards, or paper. This grasp ensures a firm hold without necessitating the closure of the entire hand, demonstrating its utility in specific gripping scenarios.

Figure 41: "Jerry" hand in lateral pinch grasp

Tripod

Falling under precision grasps, the tripod grasp (Figure 42) is facilitated by pad opposition, engaging the index and middle fingers in conjunction with the thumb. This grasp is essential for tasks demanding high levels of dexterity and precision, such as writing or manipulating small tools. This grasp closely resembles the natural position for holding a pencil, enabling nuanced control and movement.

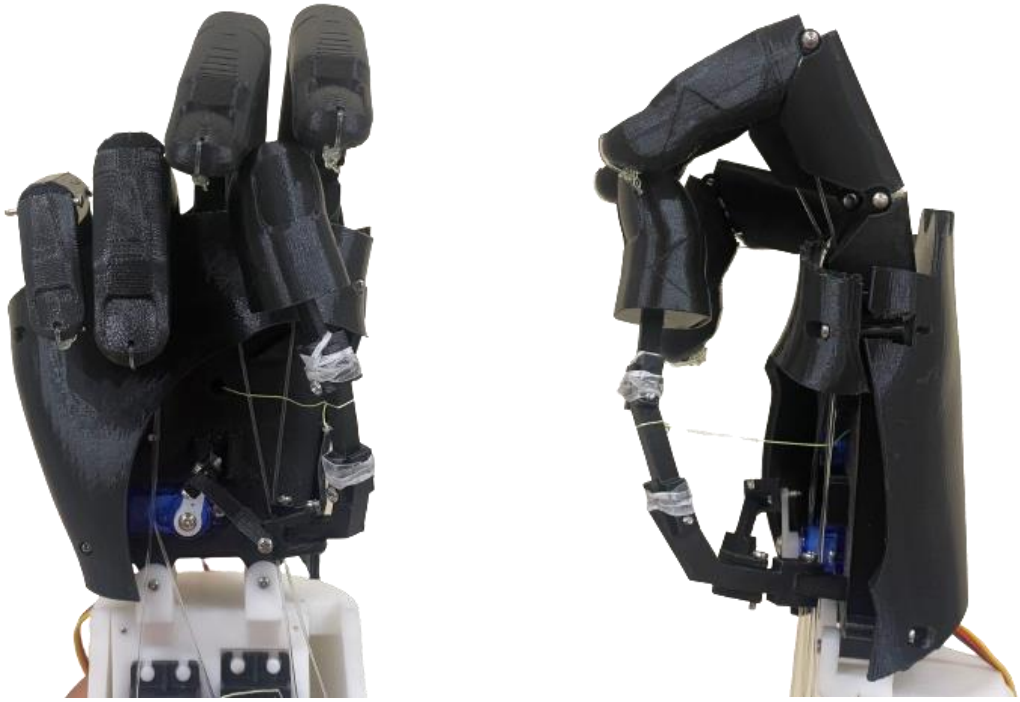

Figure 42: "Jerry" hand in tripod grasp

4.3 Testing

4.3.1 Apparatus

The testing architecture designed for evaluating prosthetic hand control utilises an advanced setup that integrates various software and hardware components to capture and analyse EEG signals generated by participants.

Matlab serves as the central hub for the testing process, orchestrating the experiment flow and participant interaction. It prompts users through the command window to initiate specific grasps, guiding the sequence of actions required during the testing phase. As participants generate EEG signals to control the prosthetic hand, they are detected by the Emotiv Insight headset. These EEG signals are then transmitted to the Emotiv BCI-OSC for classification, where the system discerns the specific mental command. Emotiv Pro runs concurrently with Emotiv BCI-OSC to record and store the raw data streamed from the headset. The classified mental commands are communicated back to Matlab using JavaOSC. Upon receiving the command, Matlab records the response times, capturing the interval from the mental command's initiation to the prosthetic hand's response. The culmination of this process is the physical prosthetic hand's reaction to the mental command. The prosthetic, connected to and controlled by the Matlab environment, physically performs the commanded grasp. This direct manifestation of the user's intent into physical action is central to evaluating the prosthetic's efficacy and the interface's overall efficiency.

4.3.2 Motor Execution Vs Action Observation

The effectiveness of EEG-controlled prosthetic systems hinges significantly on the training methods used to establish accurate mental command recognition. Two primary approaches in training EEG mental commands for prosthetic control are motor execution and action observation. Motor execution involves the user performing the grasp with their intact hand, while action observation requires the user to watch a digital twin perform the grasp. This section compares these two training methodologies in the context of developing efficient, user-friendly EEG-controlled prosthetic systems.

4.3.2.1 Motor Execution

Motor execution training capitalises on the user's own motor actions, involving the active engagement of the user in performing specific grasps or movements with their intact hand. This method is grounded in the premise that executing a motor action generates distinct neural patterns, which the EEG system can capture. Engaging the motor cortex through actual movement leads to robust and distinct EEG patterns, facilitating the accurate mapping of neural signals to specific commands[40]. This approach allows the training data to be highly personalised, reflecting the user's unique neural response to motor

actions, which can enhance the system's accuracy in recognising intended commands. Figure 43 demonstrates the principle of using motor execution to train prosthesis control.

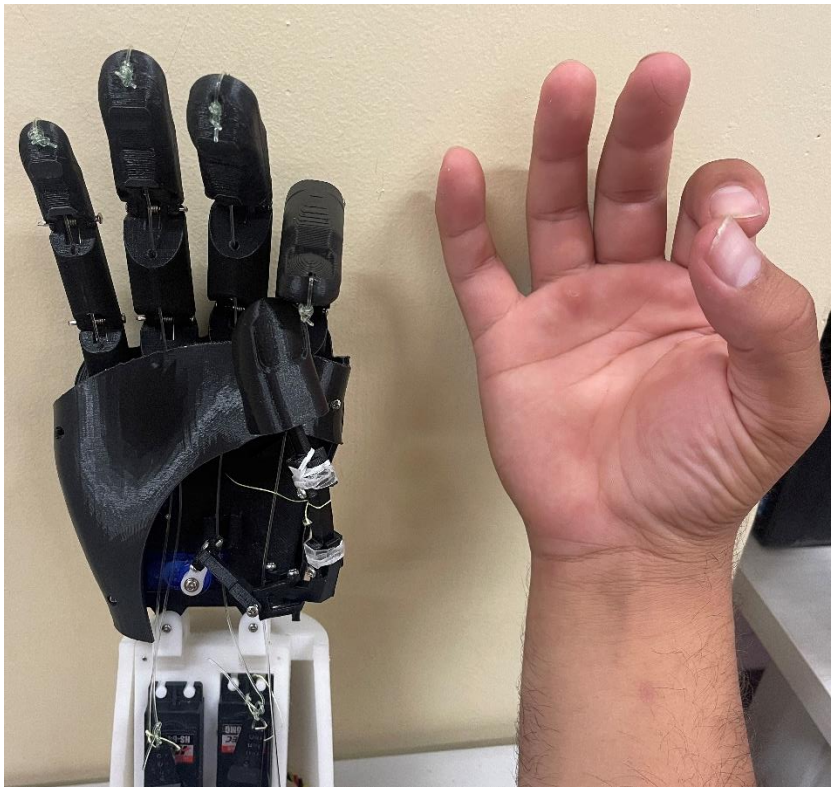

Figure 43: Demonstration of motor execution in prosthesis training

4.3.2.2 Action Observation

Action observation involves the user watching a digital twin perform the desired grasps or movements. This method leverages the mirror neuron system, which activates not only when performing an action but also when observing someone else execute the same action[40]. It provides an inclusive training option for users unable to perform physical movements, broadening the applicability of EEG-controlled prosthetics. This method allows for a wide range of grasps and movements to be demonstrated without physical exertion on the part of the user, enabling extensive and varied training sessions.

The digital twin was designed to simulate the operation of a prosthetic hand in a virtual environment. Utilising Matlab and JavaOSC, this system creates an interactive platform for users to engage with and learn the mechanics of prosthetic hand control before physical interaction. This section describes the structure and functionality of the digital twin, highlighting its components and operational flow. Two separate digital twin models were developed; a training model and real-time model.

At the core of the digital twin is a Matlab codebase that interfaces with JavaOSC, enabling the reception of input signals from the Emotiv BCI at the onset of training sessions. This establishes a seamless communication channel between the user's mental commands in Emotiv BCI-OSC and the digital twin, ensuring that the simulation responds accurately to user intentions. The core of the digital twin's training

model resides in its ability to simulate the prosthetic hand in a resting state, transitioning to active demonstration upon receiving a signal from the Emotiv BCI at the start of each training session. A countdown initiates the demonstration phase; after that, the 3D model animates the selected grasp, maintaining the position for the duration of the testing period. This serves as the stimulus for participants to engage in action observation. Figure 44 displays the digital twin of a prosthesis used for training action observation.

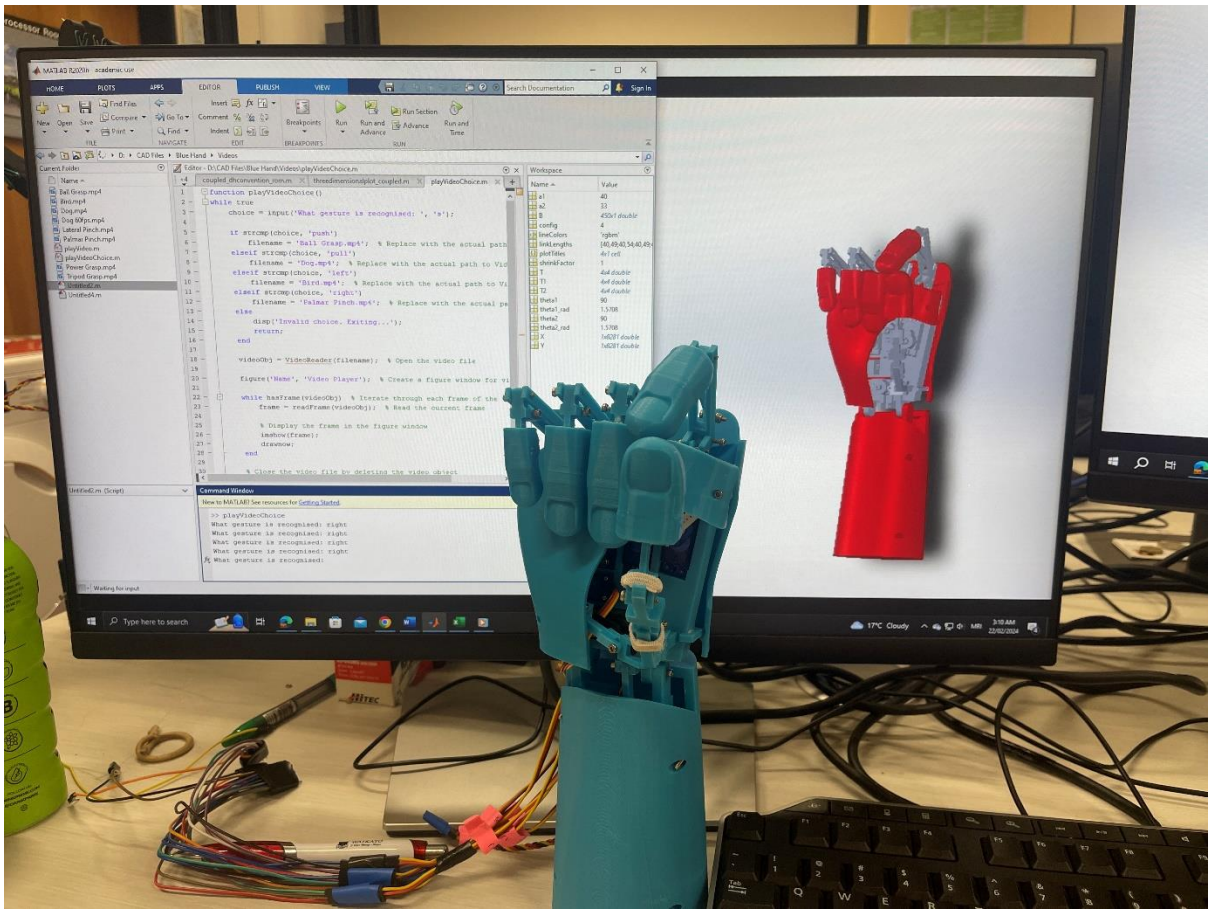

Figure 44: Demonstration of digital twin of "Dre" hand used in action observation prosthesis training

In addition to the primary training model, a supplementary real-time interaction model was developed to simulate immediate feedback in response to mental commands initiated by the user. This model dynamically animates the 3D prosthetic hand model into the commanded grasp in real time, closely mimicking the feedback loop anticipated in actual prosthetic usage. The design mandates that each grasp animation be completed and the model returned to a neutral state before recognising subsequent commands, emphasising the necessity of precise control and timing in prosthetic hand operation. While the real-time interaction model holds promise for enriching the prosthetic control training regimen, its direct application was not explored within this study.

4.3.3 Pre-training Phase and Ethics

Before the training phase commences, participants undergo a pre-training phase designed to ensure informed consent and understanding of the project's scope. Participants are presented with a project outline form that details the objectives, procedures, and expected outcomes of the study. This document serves to inform participants about the nature of the research and what their involvement will entail. Following this, participants are required to read and agree to a consent form, affirming their voluntary participation and understanding of the project's requirements and their rights as participants. This step is crucial for ethical compliance and participant safety, ensuring that all individuals are fully informed and agreeable to proceed with the study. Participants are then assigned to a test group, which will determine the type of stimulus they will use in the training phase; Group A was assigned to motor execution, and Group B was assigned to action observation. Once participants have filled out all required documents, the headset calibration and set-up occur. A saline solution is applied to all sensors to enhance conductivity, followed by careful placement of the headset on the participant's head. Special attention is given to securing a strong signal from the reference sensor and ensuring good skin contact for the PZ sensor. Adjustments are made until optimal contact quality is achieved, aiming for at least 75% EEG Quality before proceeding. A unique profile for the participant is then created in the Emotiv BCI-OSC software, marking the beginning of the data acquisition process.

This project received formal ethical approval from the Human Ethics Committee (HEC) at the University of Waikato under the application number HREC(HECS)2023#46. The approval encompasses the recruitment of participants aged between 18 and 65 years, involving up to 15 individuals, for the purpose of developing and evaluating training methodologies aimed at enhancing motor imagery capabilities for the operation of brain-controlled robotic hands. Participants are within the age range of 18 to 65 years, have no diagnosed neurological disorders, and are non-amputees of any gender. This wide demographic range is chosen to encompass a broad spectrum of neural patterns, which is vital for the robust training of the EEG system. Recruitment efforts focused on the University of Waikato, particularly communities within the Schools of Engineering, Health, and Māori. Referrals from faculty members served as the primary recruitment channel, complemented by the use of email as the main method of communication for contacting and engaging prospective participants. This approach ensures a targeted yet diverse participant pool, facilitating the study's objectives to explore and refine EEG-based control mechanisms for prosthetic hands.

4.3.4 Training Phase

The training phase is structured to capture both neutral and command signals associated with hand gestures. Participants start by training the neutral signal, adopting a relaxed state with eyes closed for 8 seconds to establish a baseline of neural activity. Following this, they engage in training specific gestures by focusing on the action while observing their specified groups stimulus. Each training session

is either accepted if the quality is above 30 or rejected. All rejected sessions are noted. The training phase is deemed complete when the participant has successfully recorded ten data points meeting the specified criteria for all four mental commands. This process ensures that the EEG-controlled prosthetic system is finely tuned to the individual's neural signatures, enabling accurate and intuitive control of the prosthetic hand.

4.3.5 Test Procedure

The testing phase of the EEG control system is designed to evaluate the precision and responsiveness of the system to user commands for various hand grasps. This section outlines the structured approach to testing, which is divided into two main series: singular grasp testing and multi-grasp testing. Each series is designed to assess the user's ability to control the prosthesis through mental commands, capturing the efficiency and accuracy of each specified grasp. Figure 45 shows the structure of the testing sequence. Testing commences with the participant in a rest state to establish a baseline for neural activity. For each test, the participant is prompted to activate the prosthesis to perform the specified grasp. A three-second countdown, accompanied by an audible cue, signals the beginning of the test, followed by an eight-second window during which the participant attempts to perform the grasp. The time taken to successfully achieve the grasp is recorded for analysis. This sequence is repeated for eight trials per test to ensure consistency and reliability in the data collected.

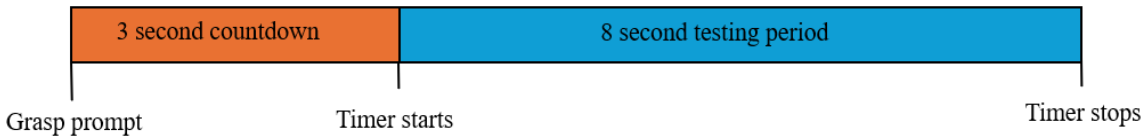

Figure 45: Structure of testing sequence.

During the singular grasp testing phase, participants focus on activating a single grasp type at a time. This phase is critical for evaluating the system's ability to accurately interpret and execute distinct commands for each grasp. The singular grasp tests encompass:

- Power grasp
- Palmar pinch (P.Pinch)
- Lateral pinch (L.Pinch)
- Tripod grasp

Participants perform a set of single grasp tests for each of these individual grasps, allowing for a focused assessment of the prosthetic's performance in executing each command.

Building upon the foundation established in the singular grasp testing, the multi-grasp testing phase introduces complexity by combining multiple grasps within a single test sequence. This phase assesses

the system's capability to differentiate and execute commands when multiple grasps are active, mirroring more realistic scenarios where users may need to transition between different grasps fluidly. The multi-grasp tests are structured as follows:

- Power grasp and Palmar Pinch
- Power grasp, Palmar Pinch, and Lateral Pinch
- Power grasp, Palmar Pinch, Lateral Pinch, and Tripod grasp

Each combination adds an additional grasp to the sequence, challenging the participant and the system to accurately identify and perform multiple grasp commands.

4.4 Results

This section presents the outcomes of the conducted tests aimed at evaluating the effectiveness and responsiveness of motor execution (ME) and action observation (AO) training methods in controlling prosthetic hands. The testing involved a total of ten participants, evenly divided, with five participants undergoing motor execution training and the other five engaging with action observation.

The accuracy of prosthetic hand control was assessed by evaluating the percentage of tests where users successfully executed the intended grasp within the specified timeframe. This accuracy metric underscores the training effectiveness and the prosthetic's responsiveness to user commands. The results of this are detailed in Table 5.

Table 5: Accuracy of training methods

	ME	**DT**
Fist	67.5%	82.5%
P.Pinch	97.5%	90.0%
L.Pinch	97.5%	82.5%
Tripod	92.5%	85.0%
Fist+P.Pinch	35.0%	40.0%
Fist+P.Pinch+L.Pinch	7.5%	2.5%
Fist+P.Pinch+L.Pinch+Tripod	2.5%	0.0%

The analysis of single grasp testing revealed varied average response times between the motor execution and digital twinning groups. A plot (Figure 46) illustrates these differences, incorporating data points that exceeded the 8-second limit.

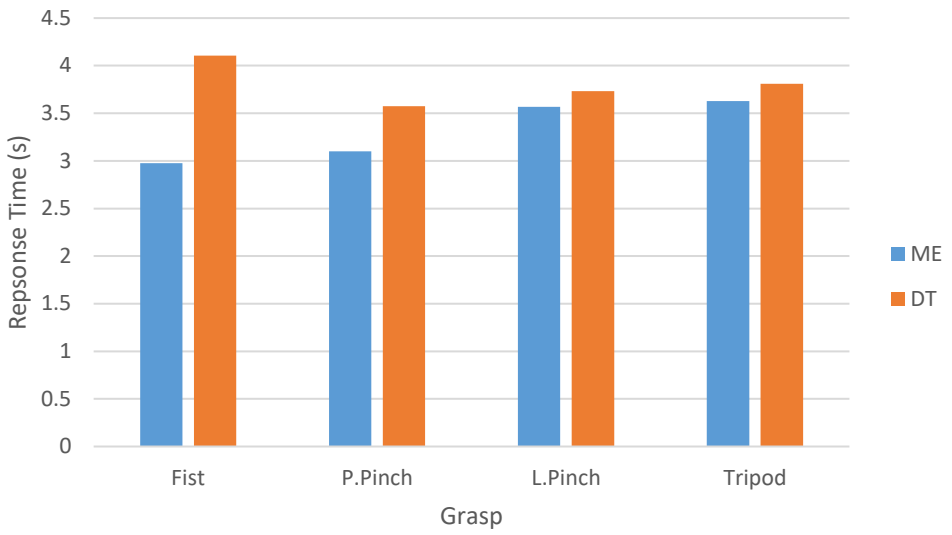

Figure 46: Average response time of single grasp testing.

For multi-grasp testing, where participants were required to execute sequences of multiple grasps, the collected data further elucidated the impact of training method on response times. Figure 47 showcases the average response times for executing multi-grasp commands, comparing the performances of participants trained via motor execution versus those trained with digital twinning. Like the single grasp results, this analysis includes all instances where the execution time surpassed the 8-second threshold.

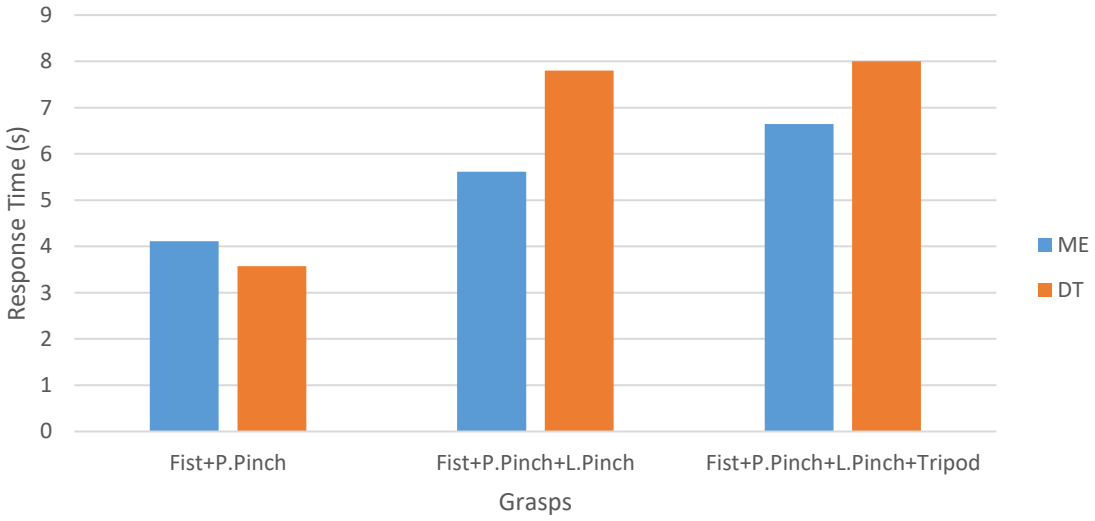

Figure 47: Average response time for multiple grasp testing

Throughout the training phase, a criterion was established that only data with a quality score above 30 would be considered acceptable for analysis. This threshold was applied to ensure the reliability and relevance of the training data. Instances of rejected training data, due to falling below the quality

threshold were recorded. This approach allowed for a clear distinction between high-quality training sessions and those deemed insufficient for further analysis. Figure 48 shows the total number and the average number of rejected training sessions for each grasp.

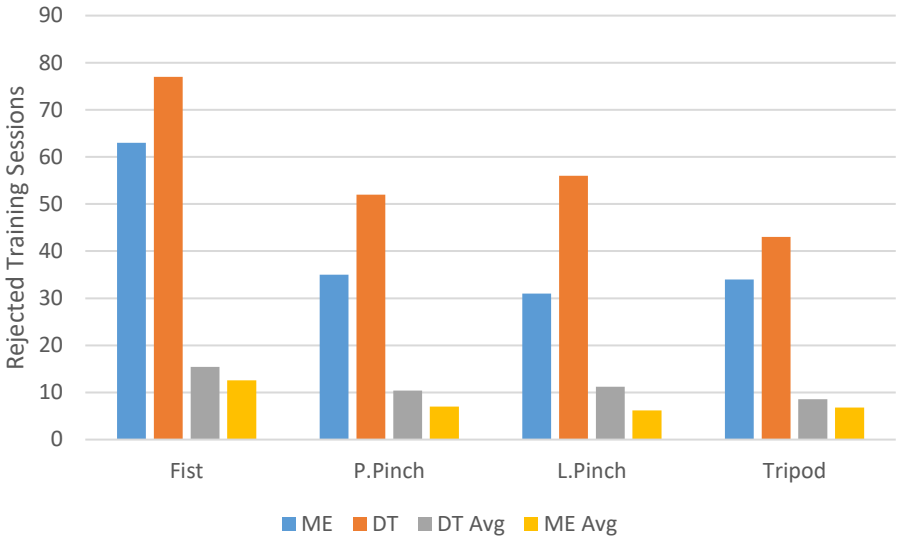

Figure 48: Number of rejected training sessions

A recurring observation was that participants frequently anticipated the grasp command during the countdown, leading to premature initiation of the grasp before the test officially began. All response times less than 0.1 seconds were considered anticipated and thus removed from the final results. Furthermore, instances were noted where participants took longer than the allotted 8 seconds to execute a grasp. Although these instances of exceeding the time limit were recorded, they were nevertheless factored into the average response time calculations to ensure a thorough representation of participant performance. These values are displayed in Table 6.

Table 6: Anticipated and time exceeded tests

	Anticipated		**Time Exceeded**	
	ME	**DT**	**ME**	**DT**
Fist	5	2	8	5
P.Pinch	1	2	0	2
L.Pinch	1	4	0	3
Tripod	2	3	1	3
Fist+P.Pinch	4	0	22	24
Fist+P.Pinch+L.Pinch	0	0	37	36
Fist+P.Pinch+L.Pinch+Tripod	0	0	39	40

4.5 Discussion

4.5.1 Analysis

The analysis of EEG data in the context of prosthetic hand control provides valuable insights into the system's performance and user interaction. This analysis specifically focuses on the accuracy of different grasps, the impact of training and testing immediacy, and the challenges associated with multiple grasp commands.

Single Grasp vs Multi-grasp

The results indicate that across both training methods the fist grasp was the least accurate among the grasp tested. Several factors could contribute to this observation. The fist grasp, being the first trained mental command, means that users had minimal experience and exposure to controlling the prosthetic via EEG at this stage. Additionally, the proximity of testing to the training session might not have allowed sufficient time for users to consolidate their learning, resulting in a smaller pool of relaxed state data. This lack of diverse data could lead to a less defined command as the system struggles to differentiate between the intended fist command and the default neural state of rest. This is reinforced by the fist grasp having the highest rate of rejected training data.

As the testing progresses to include multiple grasps, a clear trend is observed: the addition of more grasp options complicates the user's ability to select the correct grasp. This difficulty likely stems from the system's limitation in binary classification, which can lead to confusion or overlap in the user's attempt to execute distinct commands. This limitation underscores the need for advanced signal classification techniques capable of distinguishing between closely related neural patterns associated with different grasps.

Motor Execution vs Action Observation

In comparing the training methods of Motor Execution (ME) and Action Observation (DT—Digital Twinning), our analysis reveals distinct patterns in user performance, particularly concerning the time taken to trigger prosthetic commands. A noteworthy observation is the general trend of longer trigger times for users trained using AO, with a notable exception in the combination of Fist and Palmar Pinch (P.Pinch) commands. This outlier suggests that AO may facilitate higher accuracy during testing despite not showing significant differences overall. This phenomenon could be attributed to the specific design and implementation of the DT training method.

Despite the slightly longer trigger times associated with AO, the method exhibits considerable promise as a training tool. The results indicate that the performance gap between ME and AO is within a manageable percentage, suggesting that AO is a viable method for early training. This means that new prosthesis users will be able to begin their prosthesis training prior to receiving their prosthesis. This early engagement allows users to familiarise themselves with the prosthetic control systems before

receiving their physical prosthetic, potentially enhancing their skill level upon actual use. Such preliminary training could significantly impact the user's adaptation process, increasing the likelihood of consistent use and reducing the chances of prosthetic rejection.

The potential of DT as a training method extends beyond mere familiarity with the prosthetic controls. It offers users the opportunity to visualise and mentally practice the operation of their future prosthetic limbs, a factor that could contribute to a smoother transition to physical use. Early training with DT could also address psychological barriers to prosthetic acceptance, fostering a more positive and proactive attitude toward prosthetic adaptation.

4.5.2 Limitations

The exploration of EEG control for prosthetic hands reveals a potential for creating an intuitive neural interface between users and their prosthetic devices. However, this approach is not without its limitations. These range from technical constraints in the EEG hardware itself to practical challenges affecting user experience.

Limitations of EEG Control Systems

One of the primary technical limitations of this control system lies in the Emotiv Insights headset's configuration, specifically its channel count and sensor placement. Using a headset with only five channels restricts the amount of EEG data that can be collected. A greater number of sensors could enhance the system's ability to capture and classify each mental command profile, leading to improved accuracy and reliability in command interpretation. Moreover, the current sensor placement might need to be more optimal for capturing signals related to specific intentions or commands. Research suggests that targeting specific areas of the brain, such as the F3 and FC5 positions on the pre-motor cortex and frontal regions, could yield better results in detecting action intentions[73]. This highlights a gap between the ideal sensor placement for capturing the most relevant neural signals and the practical design of commercially available EEG headsets.

The system's current capability to track a single mental command scale at a time poses a significant challenge in accurately classifying user intentions, significantly as the complexity of commands increases. Investigating the relationship between performance metrics, such as user frustration or concentration levels, and the accuracy of command execution could reveal insights into performance. For instance, an increase in user frustration might correlate with decreased accuracy in command execution, suggesting that emotional and cognitive states significantly impact the effectiveness of EEG-controlled prosthetics. Understanding these dynamics is essential for developing more adaptive and user-friendly control systems.

Beyond the technical aspects, practical challenges significantly impact the feasibility and user acceptance of EEG-controlled prosthetics. Firstly, the daily requirement to wear and accurately position

the EEG headset can be cumbersome for users. Achieving the correct fit and ensuring optimal sensor contact is crucial for reliable signal acquisition but may become a barrier to routine use. Additionally, the limited battery life of wireless EEG headsets adds another layer of inconvenience, potentially interrupting usage at critical times.

Aesthetics and social acceptance play a substantial role in the adoption of assistive technologies. Unlike EMG systems, which can be seamlessly integrated into the prosthetic socket and remain out of sight, non-invasive EEG systems are worn externally and are visible to others. This visibility may make users feel self-conscious or stigmatized, as the device highlights their disability rather than enabling them to blend in.

Connectivity issues and the need for good electrode contact further complicate the use of EEG for prosthetic control. Maintaining consistent contact with the scalp is essential for accurate EEG data collection, yet everyday movements and activities can disrupt this contact, leading to signal loss or degradation. This challenge underscores the difficulty of ensuring reliable system performance in the dynamic and varied contexts of daily life.

While EEG control offers a promising avenue for enhancing the functionality and intuitiveness of prosthetic hands, addressing its limitations is crucial for advancing the technology to a point where it can meet the needs and expectations of users.

Limitations of Training and Testing Procedure

The training and testing procedures employed in this study, while yielding valuable insights, are subject to several limitations that must be acknowledged and addressed in future research. These limitations primarily pertain to the scale and scope of the data collection process, participant diversity, and the granularity of the testing feedback mechanism.

The current size of our data pool poses a limitation. The training sessions were conducted over a relatively short period, providing a limited dataset for each user. Expanding the training duration could allow users to develop more comprehensive profiles, enriched with a larger array of data points. This expansion would likely lead to the emergence of more distinct and unique mental command patterns, thereby increasing the accuracy and specificity of command recognition.

The inclusion of more participants in the study is an area for enhancement. A larger participant base would not only strengthen the statistical validity of our findings but also offer a more diverse array of mental command patterns. This diversity is essential for refining our algorithms and ensuring the system's adaptability across a wide range of individual users.

Testing within the community of upper limb amputees is another important consideration. While the current study provides valuable preliminary insights, the real-world applicability and effectiveness of the training and control system must be validated with the actual target user group. Community-based

testing would offer direct feedback on the system's performance and user experience from those who stand to benefit most from these technological advancements.

The design of the testing code presents an opportunity for improvement. Currently, it does not account specifically for instances where users trigger an incorrect grasp, nor does it identify which incorrect grasp was triggered. Enhancing the code to capture these details would provide invaluable data on common errors or misconceptions among users. This information could be used to adjust training protocols, refine the user interface, and ultimately improve the intuitiveness and reliability of the prosthetic control system.

4.5.3 Digital Twinning

This technology's versatility and capability to simulate realistic prosthetic usage scenarios offer profound benefits for users, from pre-arrival training to personalised fitting and mirror therapy. Beyond prosthetics, digital twinning's impact extends into manufacturing, energy systems, and process engineering, demonstrating its wide-ranging applications.

Digital Twinning in Prosthetics

Digital twinning stands out as a revolutionary rehabilitation tool, enhancing the training process for prosthetic users. It allows users to familiarise themselves with their prosthetic hands before physical delivery, offering a virtual environment to practice and master control systems identical to those installed in their actual prosthetics. This pre-emptive training ensures a smoother transition and quicker adaptation to the new limb, potentially reducing the overall rehabilitation period.

Furthermore, digital twins can host multiple prosthetic hand models within the same program, enabling users to trial various options. This feature is invaluable for identifying the prosthetic hand that best suits an individual's needs, preferences, and lifestyle. This ensures optimal compatibility and a higher likelihood of prosthesis acceptance.

Incorporating AR and VR technologies into digital twinning opens new dimensions of interactivity and immersion. While VR systems are noted for their intuitive interfaces, they may lead to slower reaction times compared to traditional on-screen simulations, possibly due to higher cognitive and processing demands. Despite this, the immersive experience of VR provides a compelling environment for prosthetic training.

AR technology, in contrast, is particularly promising for its ability to overlay a virtual prosthetic over the user's residual limb. This not only aids in visualising the future appearance and functionality of the prosthetic but also enhances the user's psychological readiness and acceptance of the limb. AR's potential for intuitiveness and real-life application marks a significant advancement in pre-adaptation training for prosthetic users.

Digital twinning could be used as an effective tool for mirror therapy, particularly for individuals experiencing phantom limb pain. By creating a virtual representation of the missing limb and simulating its movement, users can engage in therapeutic exercises that help alleviate the discomfort and pain associated with phantom sensations. This application of digital twinning offers a non-invasive, accessible means of addressing a common and often challenging issue faced by amputees.

Broader Applications of Digital Twinning

In manufacturing, digital twins revolutionise the design and operation of automation and robotic production lines[42]. Simulating the entire production process allows for the identification and optimisation of bottlenecks, enhancing efficiency and productivity. Furthermore, digital twinning facilitates precise analyses of energy usage and waste, enabling more sustainable manufacturing practices.

Digital twins find extensive applications in energy systems and process engineering, where they can model and optimise the performance of energy plants, distribution networks, and chemical processes[74]. This capability not only improves operational efficiency but also contributes to environmental sustainability by minimising resource consumption and waste.

Digital twinning, with its wide-ranging applications from prosthetics to manufacturing and beyond, represents a significant leap forward in technology's role in enhancing human life. In prosthetics, it promises a future where users are better prepared, more comfortable, and more satisfied with their prosthetic devices, thanks to advanced training, customisation, and therapeutic applications. As digital twinning technology continues to evolve, its potential to transform various industries and improve efficiency, sustainability, and user experience appears boundless.

4.6 Future Considerations

As we look toward the future of EEG-controlled prosthetic hands and their broader application in assistive technology, several strategic steps stand out as essential for advancing the field. These future directions aim to refine training methodologies, explore innovative technologies, and expand the capabilities of control systems for prosthetic devices. An area for development is optimising the training scheme used for users to adapt to EEG-controlled prosthetics. An enhanced approach would involve starting users with motor execution training to leverage the direct neural feedback from actual movements. This initial phase helps establish a strong foundation of neural patterns associated with specific prosthetic controls. Subsequently, transitioning users to digital twinning (DT) training can capitalise on the established neural groundwork while offering the benefits of simulation and visualisation. This phased training approach aims to combine the strengths of direct motor execution with the advanced simulation capabilities of DT, potentially leading to more rapid and intuitive adaptation to the prosthetic device.

The effectiveness of EEG-controlled prosthetics is significantly influenced by the quality and specificity of the neural data captured. Pursuing different EEG headsets, particularly those designed to capture action intention signals better, could greatly enhance system responsiveness and accuracy. Headsets with higher channel counts, improved sensor placement, or specialised sensors to detect nuanced neural patterns associated with specific intentions offer promising avenues for research. Such advancements could lead to a more intuitive and seamless interface between the user and the prosthetic, mirroring natural limb movements more closely.

Another promising future direction is the exploration of Lightmyography (LMG), a novel technique that, like EMG, measures muscle activity but does so using optical sensors rather than electrical signals. LMG presents an exciting opportunity to combine the benefits of EMG with the potential for enhanced control, particularly in terms of proportional force application. This technology could allow users to control their prosthetic devices with greater precision, offering a more natural and nuanced interaction. By accurately measuring the intensity of muscle contractions through light-based sensors, LMG could provide a more detailed and dynamic control scheme, enabling users to perform a wider range of tasks with their prosthetics, from delicate manipulations to forceful grips.

4.7 Conclusion

This chapter has successfully developed and evaluated an EEG control system designed for upper limb amputees based on the “Jerry” hand developed in chapter 3. The comparative analysis of training methodologies—Motor Execution and Action Observation—revealed that while motor execution exhibited a slight edge in performance, the distinction was not substantial enough to dismiss the value of action observation. This finding opens the door to further exploration of more immersive training environments, suggesting that digital twins enhanced with Virtual Reality (VR) or Augmented Reality (AR) technologies may yield improved training outcomes and user proficiency.

A notable limitation emerged in the classification system's performance as the complexity of user commands increased. As the variety of available grasps increased, the system's ability to accurately classify and execute the intended grasps diminished. This challenge underscores the need for ongoing refinement of the classification algorithms and system architecture to better accommodate a broader spectrum of commands without compromising accuracy.

The core aim of this research—to contribute to the enhancement of quality of life for upper limb amputees through advancements in prosthetic control systems and rehabilitation processes—has been addressed through the development of this EEG control system. By expanding the toolkit for prosthetic control beyond traditional EMG methods and exploring the potential of EEG signals, this work lays the groundwork for more intuitive, accessible, and adaptable prosthetic solutions. It not only broadens the scope of who can benefit from prosthetic technologies but also enhances the level of control and naturalness with which users can interact with their environment.

In conclusion, while this research has highlighted both the potential and the challenges of EEG-controlled prosthetics, it ultimately contributes to a larger conversation about how best to serve the needs of amputees. By pushing the boundaries of current technology and continuously seeking innovative solutions, we move closer to creating prosthetics that not only mimic natural limb function but also seamlessly integrate into the lives of those they aim to assist, thereby significantly improving their quality of life.

In addition to improving the quality of life for amputees through improved control systems this work also looks toward indigenous knowledge for guidance. The following chapter investigates how an alternative perspective, the mātauranga Māori perspective, can lend insights into the design of prosthetic hands.

Chapter 5: Mātauranga Māori Perspectives

5.1 Introduction

The development and application of prosthetics for rehabilitation have traditionally been approached from a Western perspective. The Western perspective prioritises addressing the physical effects associated with amputation and prosthetics, with a particular emphasis placed on retraining the body through physical therapy. In addition to this, appropriate prosthetic materials are selected based on their cost-effectiveness and mechanical properties, aiming to restore the lost physical function as efficiently as possible. Despite these efforts, rejection rates for prosthetic limbs remain notably high. This would suggest that a purely functional focus is not sufficient to meet the needs and challenges faced by amputees.

A Māori perspective on the same issue would not necessarily produce the same emphasis on purely physical outcomes. For example, Durie postulated that the Māori perspective of health can be represented as a wharenui (meeting house) with four equal walls. Each wall representing a different dimension of wellbeing; taha tinana (physical well-being), taha wairua (spiritual well-being), taha whānau (family well-being) and taha hinengaro (mental well-being)[64]. The Te Whare Tapa Whā perspective suggests that should one of the four dimensions be missing or in some way damaged, a person, or a collective may become ‘unbalanced’ and subsequently unwell. Based on the premise of Te Whare Tapa Whā there is unexplored territory that exists with respect to the Incorporation of Māori perspectives into prosthetic design. This integration promises to extend the scope of prosthetic functionality to encompass not only the physical but also the emotional, social, and spiritual well-being of the user. Such an approach advocates for prosthetic solutions that resonate with the user's cultural identity and personal values, potentially reducing rejection rates by addressing the broader spectrum of amputee needs. As a result this work offers a novel and valuable perspective that has yet to be fully explored in the field of rehabilitation for upper extremity amputees.

The following chapter will explore key concepts within te ao Māori, by providing a background on the importance of mātauranga Māori, whakapapa (genealogical connections) and pūrākau (narratives) . These concepts provide a rich tapestry of understanding that is integral to the Māori worldview. After defining these concepts two pūrākau described and examined to identify their value in contributing to prosthetic device development. Next a discussion of how mātauranga Māori could be used to influence prosthesis design takes plac followed by a recognition of the limitations and challenges associated with incorporating mātauranga into the field of prosthetic device development. Finally, the chapter conclude by outlining the main learnings and finding of the chapter.

5.2 Background

Mātauranga Māori, the repository of Māori knowledge, wisdom, and understanding, forms the bedrock of the Māori cultural identity. It encompasses an intricate blend of historical, environmental, spiritual, and practical wisdom passed down through generations[75]. This holistic body of knowledge is not merely academic; it is a living, breathing guide for engaging with the world, deeply entwined with the Māori way of life. It emphasizes the interconnectedness of all beings and insists on a balanced relationship with the natural world, laying a foundation for understanding the universe and our place within it.

Central to navigating the complexities of mātauranga Māori is the concept of whakapapa. Whakapapa is a cognitive genealogical framework which establishes interconnectedness between all elements of the universe and traces lineage back to ancestral origins [76]. As a result, whakapapa is considered foundational knowledge in the Māori perspective of the world. In addition to the oral tradition of whakapapa we also consider pūrākau. Whakapapa is the genealogical thread that weaves individuals into the broader fabric of the universe, connecting them to their ancestors, the atua, and all elements of creation. It transcends the notion of lineage as a merely biological connection, presenting it as a comprehensive map of relationships that tie humans to the land, the sky, and the myriad forms of life that inhabit the earth. This interconnectedness, as articulated through whakapapa, reinforces the responsibilities individuals hold towards their ancestors and descendants, and it highlights the symbiotic relationship between people and the environment.

One important way of conveying whakapapa is through Pūrākau, narratives of the Māori world. Pūrākau are imbued with teachings, wisdom, and insights into how Māori understand the world. Through pūrākau, the actions of ancestors are recounted, offering lessons on ethics, leadership, and the natural laws of the universe. These narratives bind the present to the past, ensuring that life lessons are not lost but continue to inform and guide future generations in their interactions with the world around them. Pūrākau additionally contain profound philosophical insights, epistemological constructs, cultural codes, and worldviews [77]. While some may label these narratives as myths or folklore, such interpretations undermine the ontological and epistemological significance of pūrākau in teaching, learning, and the intergenerational transmission of knowledge [78]. The tradition of understanding phenomena through storytelling has been a longstanding and integral practice within Māori culture.

Within the Māori world view, mauri emerges as a critical concept, representing the life force or essence that permeates everything in the universe. Mauri is what animates the physical and spiritual worlds, ensuring harmony and vitality[79]. The health and well-being of individuals and the environment are thus seen as intrinsically linked to the state of mauri, with practices aimed at preserving or enhancing this vital essence considered paramount. The concept of mauri not only underscores the Māori commitment to environmental stewardship but also emphasizes the spiritual nature of existence.

Furthermore, the principles of tapu and noa further illustrate the Māori approach to managing the sacred and the secular, playing a pivotal role in the daily life and spiritual practices of Māori. Tapu, with its implications of sacredness and restriction, sets boundaries that protect the mauri of individuals, communities, and the natural world. Noa, in contrast, represents the state of being ordinary or free from the constraints of tapu, allowing for the everyday flow of life[79]. The dynamic interplay between tapu and noa ensures that the sacred is respected while life continues in its myriad of forms. Through rituals and adherence to these principles, balance is maintained, reinforcing the harmonious relationship between the spiritual and physical realms.

As we traverse the landscape of mātauranga Māori, from the foundational knowledge systems to the connections articulated through whakapapa, the narrative power of pūrākau, the life-affirming essence of mauri, and the regulatory principles of tapu and noa, a comprehensive picture emerges. This tapestry of knowledge and connection offers not just a glimpse into the Māori worldview but also a model for living that emphasizes balance, respect, interconnectedness, guiding principles that are ever increasingly relevant in our global quest for sustainability and harmony.

5.3 Pūrakau

Pūrākau unveil the interplay between mātauranga Māori, and the holistic comprehension of the cosmos, serving as catalysts for exploration and insight into the connections that underpin Māori culture and identity. This section will introduce two pūrākau that serve as pillars supporting the themes explored in this work. Specifically, this section will outline and describe the separation of Ranginui and Papatūānuku, the sky father and earth mother, as well as the the creation of Hineahuone, the first woman. This work will delve into the nuances of these specific pūrākau and their intersections with contemporary research. Through the lens of these narratives different perspectives, rooted in mātauranga Māori, can be identified to improve the design and development of assistive technology.

5.3.1 The Separation of Ranginui and Papatūānuku

In the primordial epoch, the divine entities Ranginui, the celestial father, and Papatūānuku, the earth mother, existed in a profound embrace, enveloping their offspring in perpetual darkness[80-82]. This intimate union constrained the world in an obscure stillness, stifling growth, movement, and understanding. Their progeny, dwelled in this shadowy realm, content yet curious about the possibilities beyond the confines of their parents' embrace. As time passed, a sense of discontent crept into the hearts of these deity, with some yearning for change and exploration. Numerous discussions ensued, with fervent debates on the prospects that lay beyond their current existence. Eventually, the decision was made to separate Ranginui and Papatūānuku, allowing them to venture into the unknown. Tāne, one of the divine brothers, assumed the task of executing this momentous division. He positioned his head upon Papatūānuku and extended his limbs, pushing against Ranginui with great force until, amidst

groans and cries, the mighty bodies of Ranginui and Papatūānuku were forced apart. The rituals and wisdom of the tohunga, Pāia, played a crucial role in this separation. Ranginui was elevated onto Pāia's back, and as a result, te ao Marama, the realm of light and day, was introduced into the world. In the aftermath of this cosmic separation, conflicting emotions arose among the divine beings. Some harboured resentment and remorse, viewing the act as a mistake, while others embraced the opportunities their newfound autonomy brought. Ranginui and Papatūānuku bore over 70 children, each of whom would go on to claim dominion over different aspects of the world. Among these prominent deities are Tangaroa, the god of the sea; Tāwhirimātea, the god of winds and storms; Tāne Mahuta, the god of forests and birds; Tūmatauenga, the god of humans and war; Haumia-tiketike, the god of wild foods; Rongomatane, the god of cultivated foods; Rehua, associated with stars and the heavens; and Ruaumoko, the god of earthquakes and volcanoes. These atua, with their distinct domains and characteristics, embody the intricate connections between nature, humanity, and the spiritual realm in Māori cosmology. Their roles, talents, and responsibilities are interwoven with their whakapapa, linking them back to Ranginui and Papatūānuku, and further emphasizing the unity and continuity of the Māori worldview.

The Māori cosmogony exemplifies the concept of whakapapa through the emergence of the children of Ranginui and Papatūānuku into te ao Mārama (the world of light and consciousness). This event represents a pivotal moment in Māori cosmology, symbolizing the transition from darkness and potentiality to a realm of awareness and existence. This narrative underscores the interconnectedness of all life forms, as the offspring of Ranginui and Papatūānuku and encapsulates the concept that bind all entities within the Māori worldview.

5.3.2 The Creation of Hineahuone

The pūrākau of Hineahuone's origin holds deep significance for Māori, shedding light on the beginnings of human existence. According to Te Mātorohanga, the tale follows Tāne and his brothers who gathered at Kurawaka, a place symbolizing fertility, following Tāne's search for the missing female element [81, 82]. In his quest, Tāne sought his father Ranginui's guidance, which led him to Kurawaka. Here, the brothers collected red clay to form the body of a woman. Collaboratively, the atua played distinct roles in this creation process. The elder atua sculpted the initial body, while the younger added details such as flesh, fat, muscles, and life force. Pāia skillfully crafted the bones, forming the structural foundation. Tūmatauenga and Te Akaaka-matua worked together to shape the intricate network of muscles, ligaments, cartilage, and tendons, enabling movement and function. Rehua contributed the life-sustaining blood, wairua (spirit), and manawa ora (breath of life). Tāne's final touch involved breathing life into the sculpture, granting her consciousness. The name Hineahuone, which Tāne bestowed upon her, translates to "woman formed from earth." This name reflects her origins and the connection between humans and the land. This story is not only the tale of human creation but also a living

whakapapa. This pūrakau is a foundational aspect of mātauranga Māori, intricately weaving together human anatomy and existence. It highlights collaboration, divine contributions, and the interwoven nature of Māori cosmology [81, 82].

Together, the pūrakau identified intertwine, reflecting Māori values of collaboration, origin, and unity across both te ira atua (the celestial realm) and te ira tangata (the human realm). These narratives establish the relationship between humans and the divine realm, our origin and our potential. The Separation of Ranginui and Papatūānuku establishes the context for the creation of Hineahuone, embodying the continuum of connection and collaboration that defines the Māori worldview. Just as the division of Ranginui and Papatūānuku introduced light into the world, the emergence of Hineahuone symbolizes the interconnectedness of humanity with the land, the divine, and the narratives that shape their existence. These stories, woven with reverence and meaning, offer a profound lens through which Māori view the world.

5.4 Discussion

Mātauranga Māori provides the foundation whereon whakapapa and pūrākau stand. This section presents and discusses how the ideas and perspectives conveyed in the previously identified pūrākau can influence the design and development of prosthetic hands by connecting the origins of human creation to our desires as practitioners and designers to mimic the human hand. In order to do this, the idea of divine heritage is expressed, explained and elucidated. Following this, connections are drawn between mātauranga Māori and how it can influence the mechanical design and control systems of a prosthetic hand.

The concept of Māori having a divine heritage originates from the previously introduced pūrākau of Hineahuone. This pūrākau illustrates the creation of Hineahuone and humans through the contribution of distinct elements gifted by atua. By tracing the whakapapa, or genealogical connections, of the gifted elements, a lineage emerges that interweaves the origins of Māori people with the divine realms. According to this narrative, Hineahuone stands as the first female figure, symbolizing the inception of humanity. In a contemporary context, modern-day Māori perceive themselves as literal descendants of Hineahuone, thus embracing a divine heritage that links them to the atua, the source of their physical creation and spiritual origin. This lineage solidifies the notion that humans are inheritors of a sacred legacy, reinforcing the idea of a divine heritage that transcends time and shapes their worldview. The perception of oneself as originating from a divine source carries implications for one's perspective of the world. Embracing the belief in a divine heritage can infuse life with a sense of purpose and significance. Individuals who hold this belief often see their existence as a part of a grander cosmic plan, fostering a guiding compass for their decisions, actions, and life's trajectory. Such a sense of purpose

not only deepens personal understanding but also shapes an individual's sense of place in the broader scheme of existence.

Central to this belief is the notion of interconnectedness, where every facet of creation is inherently linked. This holistic outlook encourages viewing the world as an intricately woven tapestry of interdependence. In turn, this interconnected perspective nurtures empathy, underscores ethical principles, and influences behaviour towards a harmonious coexistence with others and the environment. This notion of interconnectedness supports the ideas put forth by Te Miri Rangi who points out that the physical body, according to Māori belief, is not simply an isolated collection of individual parts, but rather a complex network of interconnected relationships[62]. From this perspective, parts of the body such as the lungs, muscles, bodily fluids, mind, and spirit, cannot be isolated and treated separately. This realization of interconnectedness highlights the critical insight that the design of assistive devices must encompass the mental, social, spiritual, and physical dimensions of individuals. For instance, the prevalent high rates of rejection in current prosthetic devices could stem from their limited focus on the physical loss experienced by amputees, thereby disregarding the broader spectrum of effects. The narratives of mātauranga Māori shed light on the depth of these considerations, prompting practitioners and designers to reevaluate methodologies. Leading to the fundamental question: How can these multifaceted dimensions be integrated into the design process to address the comprehensive well-being of individuals? This line of inquiry propels us toward uncharted terrain, fostering exploration, interrogation, and the potential transformation of the domain of assistive device design.

Furthermore, perceiving oneself as possessing divine potential can open the door to new conversations about what is or isn’t possible. Or even about how or why things work the way they do. These discussions maybe philosophical and considered outside the scope and conventional scientific discussions but can offer alternative perspectives that complement and enrich the existing body of knowledge. In totality, the belief in originating from a divine source offers a panoramic view of the world, imbuing life with purpose, interconnectedness, humility, gratitude, service, and the pursuit of greater understanding. This expansive outlook enriches the tapestry of human experience, contributing unique threads to the intricate fabric of existence.

Leaning on the knowledge established in the pūrākau of Hineahuone, an approach toward prosthetic hand design is considered. Three atua can provide inspiration for the bio-mechanical design of the hand, Pāia, Tūmatauenga and Te Akaaka-matua. Pāia skillfully crafted the bones of Hineahuone, while Tūmatauenga and Te Akaaka-matua worked together to shape the intricate network of muscles, ligaments, cartilage, and tendons, enabling movement and function. Pāia provided twenty-seven bones including the carpals of the wrist. These bones form the skeleton of the hand. Tūmatauenga and Te Akaaka-matua contributed thirty-four muscles to activate these bones. Over half of these muscles are extrinsically located in the forearm. The other muscles are intrinsic and located within the palm of the

hand. Actuation and movement of the human hand originates from the contraction of muscles, which displaces tendons attached to the bones of the hand. The linear motion provided by the muscle creates torque at the joints of the hand. Ligaments and pulleys support the tendons of the hand, which create structures and networks throughout the hand and forearm. Understanding this orchestration of muscles and how they translate linear muscle motion into joint torque allows for the emulation of natural hand gestures. These insights allow practitioners a glimpse into the origin of the body from a Māori perspective and can guide design choices when considering the technical and mechanical properties of prosthetic hands.

Mauri was highlighted as an important consideration to the mātauranga Māori perspective. From the Hineahuone pūrakau, it was noted that when each of the atua contributed to Hineahuone's body, they embued their gifts with their own mauri. As a result, Māori share a connection with both the atua and the environment through their mauri. The disruption caused by limb loss extends beyond the physical, impacting the mauri and, by extension, an individual's overall well-being. While current prosthetic technologies are designed to restore physical function, they often overlook the spiritual dimension, potentially contributing to the high rates of prosthetic rejection observed among users. From a mātauranga Māori perspective, the pathway to reducing these rejection rates lies in creating prostheses that restore physical capabilities and re-establish the mauri disrupted by limb loss. Such an approach would entail designing prosthetic solutions that are not merely functional extensions of the body but also resonate with the spiritual and emotional aspects of the individual, fostering a more profound sense of harmony and integration. By acknowledging and incorporating mauri into prosthetic design, there is potential to enhance acceptance and satisfaction among users. This stance offers a more comprehensive approach to rehabilitation that aligns with the principles of mātauranga Māori.

In addition to the learning the origins of specific body parts there is additional value in considering appropriate materials for prosthetic hand development. Just as the body functions optimally when its components are in harmony, prosthetic devices too can achieve greater effectiveness when their constituent materials are selected carefully for their physical properties and holistic relationships. Consideration of the atua associated with a material can impact the material selection process. For instance, when designing a prosthetic device where various composite FDM 3D printer filament could be suitable, the Hineahuone pūrākau provides inspiration. Hineahuone was fashioned from earth enriched with the mauri of Papatūānuku. In alignment with this narrative, a clay-based filament could be selected to acknowledge the creation of Hineahuone. This would foster a deeper connection between the material, its origin, and the prosthetic device's purpose. Another perspective for material selection could involve Tane, the atua responsible for breathing life into Hineahuone. Exploring the use of wood-based or plant-based filaments becomes particularly intriguing given his domain over the forest. An approach by Stoof et al. involves integrating harakeke into a natural fibre-reinforced composite 3D printer filament [83]. This method exhibits a 5.4% average increase in tensile strength at a 20 wt %

harakeke content, compared to the more commonly available PLA filament. Greensill et al. also delves into the tikanga associated with 3D printing using this filament [84]. This proposition takes on fascinating dimensions, as a Māori amputee could have harakeke harvested from their own whenua (land), transforming it into 3D printing filament to craft a personalized prosthetic device. This direct connection to their land would significantly strengthen the mauri of the prosthesis could lead to lower rejection rates, foster a stronger sense of identity, and establish a more profound bond between the individual and their assistive device.

Although many aspects of the design process for the six evaluated hands did not initially draw direct influence from mātauranga Māori, the incorporation of Māori elements emerged retrospectively. For instance, the methodology devised for finger extension in “Tuarua” found inspiration from the pattern of crossing elastics, mirroring the insertion of the extensor hood around the bone. This choice not only enhanced lateral stability but also closely emulated the nuances of human anatomy. Interestingly, this approach produced an extensor hood for the hand that closely resembled the tukutuku panels found in wharenui. This design decision wasn't initially guided by Māori cultural considerations but emerged from an anatomical perspective. This point is however challenged by the fact that Māori considerations would include anatomical perspectives as evidenced from the pūrākau of Hineahuone. From a different angle, it's plausible that a latent inspiration from tukutuku patterns subconsciously influenced the design. Although not a deliberate cultural alignment, this reflection of indigenous artistry may have contributed to the uniqueness of the design process. In retrospect, the design produced a metaphorical philosophy that the elastics became a symbol of the interweaving of the “Tuarua” hand with an individual's nervous system, facilitating a sense of wholeness for the amputee.

The utilisation of EEG technology as a potential solution for prosthesis control systems presents a complex challenge that intersects and conflicts with the concept of tapu. While EEG offers promising benefits, it also brings forth a consideration involving the sacredness and reverence associated with the head. While the pūrākau of Hineahuone does not explicitly attribute the creation of the brain to one specific atua, Hanara et al. points out that the head serves as a vessel containing one's intellect, fashioned by Haematua, Roiho, Roake, and Haepuru [68]. These are celestial beings of the upper heavens, known as whatukura. These atua bestowed thought and mahara (intellectual prowess).

The head holds the highest level of tapu and is closely connected to an individual's mana (prestige) [79]. Commercially available EEG sensors are primarily designed as headsets, recording data when placed on the user's scalp. The introduction of EEG technology might engender reservations among Māori individuals due to the requirement for the technology to be worn on the head. Consequently, there could be potential resistance within the Māori community when embracing such technology [85]. This duality of tapu and mana underscores the sensitivity of this issue. This raises an ethical issue to consider when

working with EEG. To incorporate EEG into assistive device control systems while respecting Māori values, it is imperative to consider tikanga thoroughly.

5.5 Challenges and Limitations

Although this study offers valuable insights for assistive device design and broader academic research, integrating mātauranga Māori into academic practices has encountered notable challenges and limitations. This section delineates some of these hurdles, shedding light on the complexities of incorporating indigenous knowledge into scholarly discourse.

Due to the oral nature of te reo Māori, the availability of written records remains limited. This presents a series of complexities for academic research. While numerous iwi may share analogous pūrākau, intricate nuances diverge based on the iwi recounting them. The conventional Western scientific model necessitates meticulous source referencing by researchers. Herein lies a fundamental issue concerning the authorship of these pūrākau. In accordance with Article 2 of Te Tiriti o Waitangi, pūrākau are regarded as taonga (treasures)[86]. As a result, a challenge arises in identifying the authors of these narratives and in finding suitable methods for their proper referencing. This challenge highlights a constraint within the paradigm of Western science when striving to genuinely incorporate and reflect mātauranga Māori.

The effects of colonization had a profound impact on mātauranga Māori. The Doctrine of Discovery, a colonial legal framework, played a significant role in justifying European claims to indigenous lands and resources[87-89]. This doctrine, rooted in the Age of Exploration, legitimized the colonization of indigenous territories based on the premise that non-Christian lands were unclaimed and could be rightfully acquired by European powers. In the context of Aotearoa (New Zealand), this doctrine facilitated the dispossession of Māori land and disrupted their traditional way of life. The resulting cultural dislocation, loss of sovereignty, and suppression of indigenous knowledge deeply impacted Māori, leading to the erosion of ancestral practices, narratives, and holistic understandings of the world. The Doctrine of Discovery stands as a stark reminder of the injustices perpetuated during colonization and the ongoing efforts to restore, preserve, and honour indigenous knowledge and heritage.

In addition to this, the Tohunga Suppression Act of 1907 stands as a pivotal and damaging historical event for mātauranga Māori[90]. The primary intention behind this legislation was to restrict the use of traditional Māori healing practices that carried supernatural or spiritual elements. The context of this act emerged from concerns surrounding the practices of certain self-appointed tohunga who exploited superstitions, often traversing various pā (settlements) with claims of curing diverse illnesses. Controversially, the Tohunga Suppression Act has been criticized as potentially breaching the Te Tiriti O Waitangi by suppressing traditional Māori wisdom, deemed a taonga (treasure) promised to Māori under the Treaty. Tragically, this led many knowledgeable practitioners to conceal their expertise,

refraining from imparting their wisdom to the succeeding generation. Since mātauranga Māori had been predominantly transmitted through oral tradition, a significant portion of this knowledge was irretrievably lost to the annals of time. This serves as a reminder of the impact colonisation has had on indigenous knowledge systems such as mātauranga Māori.

Similarly, the Native Schools Act, enforced in the late 19th and early 20th centuries, aimed to assimilate Māori children into Western norms and practices by imposing English education and suppressing the use of the Māori language [88, 89]. This policy profoundly affected the erosion of tikanga and mātauranga Māori, as it disconnected younger generations from their ancestral knowledge systems. The suppression of te reo Māori and cultural practices in these schools further weakened the indigenous knowledge base, interrupting the intergenerational transfer of essential wisdom.

In tandem, these policies collectively led to the fragmentation, loss, and dilution of mātauranga Māori. The suppression of cultural practices, spiritual knowledge, and traditional education not only marginalized the Māori people but also underscored the resilience and strength required to reclaim and revitalize the unique knowledge systems in the face of colonial adversity. The intricate interplay of historical legislation, oral transmission, and cultural significance demonstrates the complex landscape in which mātauranga Māori navigates within the realm of academic research. As scholars embark on this journey of integration, they are confronted with the task of acknowledging these complexities and devising thoughtful approaches to bridge the gap between indigenous knowledge and established research paradigms. In this context, the significance of the work presented in this report becomes even more pronounced. By integrating mātauranga Māori into contemporary domains like prosthetic device design, this effort not only acknowledges the past injustices but also seeks to bridge the historical gaps, reaffirming the intrinsic value of indigenous wisdom.

5.6 Conclusion

This section has presented the mātauranga Māori perspective and how it can be applied to the field of prosthetics. Through this investigation two pūrākau have been identified in the context of prosthetics: the separation of Ranginui and Papatūānuku and the creation of Hineahuone. These narratives offer insights into the Māori worldview, regarding concepts of whakapapa and mauri and how they relate to the experience of limb loss.

The separation of Ranginui and Papatūānuku lays the foundation for understanding the interconnectedness of all beings, emphasizing the importance of whakapapa, which bestows upon us a divine heritage and connects us to the atua. This connection underscores the notion that limb loss affects not just the physical body but also the mauri of the individual, disrupting their spiritual and emotional wellbeing. The creation of Hineahuone from the earth highlights the sanctity of materials used in the making of prosthetics. It suggests that considering the whakapapa of the materials and the mauri of the

atua whose domain they originate from can significantly impact the design and functionality of prosthetic devices. Such an approach not only respects the cultural beliefs and values but also potentially enhances the connection between the user and the prosthetic.

A pressing issue in the integration of EEG systems for prosthetic control is the concept of tapu. The placement of EEG sensors and the extraction of neural signals touch upon deeply held beliefs about the head's sacredness and the protection of personal and spiritual integrity. Navigating these considerations requires a sensitive and inclusive approach, ensuring that technological advancements do not infringe upon cultural values.

By incorporating Māori perspectives into the development and evaluation of prosthetic technologies, this work contributes to a more holistic understanding of wellbeing that extends beyond physical health. Recognizing the importance of whakapapa, mauri, and tapu in the design process aligns with the aim of creating prosthetics that not only restore physical capabilities but also honour and reinforce the user's cultural identity and spiritual health. This approach fosters a deeper sense of acceptance and integration, offering a pathway towards improving the quality of life for Māori and other indigenous users of prosthetics, in harmony with their cultural beliefs and values.

Chapter 6: Conclusion

This project embarked on a comprehensive journey with the aim of enhancing the quality of life for amputees, by adopting a multifaceted approach that integrates prosthesis design, advanced control systems, and insights from mātauranga Māori. This research aimed to broaden the horizon of prosthetic technology and its application. This conclusion synthesizes the key findings and contributions across these dimensions, reflecting on their collective impact on improving prosthetic functionality, user control, and cultural responsiveness.

The development and assessment of four low-cost prosthetic hands marked a significant stride towards more accessible and functional prosthetic solutions. Through evaluation of their DoF, RoM and Kapandji scores, this project highlighted the attributes that contribute to a prosthetic hand's operational effectiveness. Underactuated tendon-driven systems tended to have a greater DoF and RoM which was optimal for adaptive grasping. However, this also increased their complexity and resulted in a less predictable end effector path than the coupled systems. A notable innovation proposed is the hybrid coupled-tendon finger system, which amalgamates the adaptability of underactuated designs with the precision of coupled mechanisms, promising enhanced grasp versatility and control. These findings contribute to improving the function of prosthetics.

A pivotal aspect of this project was the development of an EEG control system designed for prosthetic hand operation. This exploration into brain-controlled prosthetics included the investigation of two training regimes: motor execution and action observation through the use of a digital twin. These results show that the current state of non-invasive EEG is not suitable for everyday prosthesis control. While revealing the classification system's limitations in handling multiple active grasps, the research also underscored the potential of AR/VR-based training environments and lightmyography as avenues for future exploration. These findings underscore the need for innovative training and control strategies to make prosthetic use more intuitive and effective for upper limb amputees.

By delving into the rich tapestry of Māori perspectives through pūrakau, this project illuminated the profound implications of integrating indigenous knowledge systems into prosthetic development. The exploration revealed the significance of divine heritage, the concept of mauri in body parts, the whakapapa of materials, and the relevance of tapu in the context of EEG systems. The perspective of Māori having a divine heritage changes the approach to designing effective prosthetics. Designers must consider the whakapapa and the mauri of materials to increase the users sense of belonging. Tapu was highlighted as an ethical concern with EEG control systems as without contact with the head EEG control is not feasible. These insights offer a nuanced understanding of the cultural dimensions that influence prosthetic design and use, advocating for a more holistic and inclusive approach to prosthetic technology.

In conclusion, this project not only advances the technical and functional aspects of prosthetics but also enriches the discourse on prosthetic development with cultural depth and sensitivity. Bridging the gap between cutting-edge technology and traditional wisdom lays the groundwork for future innovations that are physically effective, culturally resonant, and spiritually meaningful. The journey towards improving the quality of life for amputees continues, with this project contributing a significant milestone that encompasses technical excellence, user empowerment, and cultural inclusivity.

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Glossary

G1 Technical Terms

Abduction: The movement of a limb or other part away from the midline of the body, or from another part.

Action Observation: Learning or enhancing motor skills by observing actions performed by others.

Action Potential: A rapid rise and subsequent fall in voltage or membrane potential across a cellular membrane with a characteristic pattern.

Adaptive Grasping: The ability of a device to conform to the shape of the object being grasped.

Adduction: The movement of a body part toward the body's midline or the movement of a digit toward the axis of a limb.

Age of Exploration: A period from the early 15th century and continuing into the early 17th century, during which European ships travelled around the world to search for new trading routes and partners.

Anthropomorphic: Designed or functioning in a way that resembles human characteristics.

Arduino IDE: An integrated development environment for programming Arduino boards.

Arduino Uno Microcontroller: A microcontroller board based on the ATmega328P, widely used for building digital devices and interactive objects.

Axial Rotation: The rotational movement of the thumb around its longitudinal axis, enabling it to oppose or touch the tips of other fingers for effective grip and manipulation.

Biomimicry: The design and production of materials, structures, and systems inspired by biological entities and processes.

Brainstem: The central trunk of the brain, continuing downwards to form the spinal cord.

Carpal: The eight small bones that make up the wrist, connecting the hand to the forearm.

Carpometacarpal Joint: The joint between the carpal bones of the wrist and the metacarpal bones of the hand.

Central Nervous System: The complex of nerve tissues that controls the activities of the body, comprising the brain and spinal cord.

Cerebellum: The part of the brain at the back of the skull, which regulates muscle movements and maintains posture and balance.

Cerebrum: The largest part of the brain, responsible for voluntary actions, speech, senses, thought, and memory.

Coupled: Linked or connected, in mechanics, describing elements that are controlled together.

Degree of Freedom: The number of independent movements or parameters that define the state of a physical system.

Denavit-Hartenberg Convention: A standardized method to describe the joint geometry of robotic arms.

Digital Twin: A virtual representation of a physical object or system across its lifecycle, used for simulation, analysis, and control.

Distal Interphalangeal Joint: The joint between the intermediate and distal phalanges of the fingers and toes.

Distal Phalanx: The last bone in each finger and toe, furthest from the hand or foot.

Distal: Situated away from the centre of the body or from the point of attachment.

Doctrine of Discovery: A concept of public international law regarding the power of a sovereign state to acquire territory through discovery and claim of uncharted lands.

Electroencephalography: A method to record electrical activity of the brain.

Electromechanical: Relating to devices or systems that involve both electrical and mechanical processes.

Electromyography: A technique for evaluating and recording the electrical activity produced by skeletal muscles.

Emotiv BCI-OSC: Software by Emotiv that allows for brain-computer interface operations, including signal processing and command classification.

Emotiv Insight: A commercial brain-computer interface device that uses EEG signals for various applications.

Emotiv Pro: Software provided by Emotiv for advanced brain-computer interface applications, including data recording and analysis.

End Effector: The part of a robotic arm designed to interact with the environment.

Extension: An increase in the angle between the bones of a joint.

Extensor Hood: A fibrous expansion over the back of the base of the phalanges of the fingers, through which the tendons of the extensor muscles insert.

Flexion: The action of bending or the condition of being bent, especially of a joint or limb.

Fused Deposition Modelling: An additive manufacturing process that uses a continuous filament of a thermoplastic material.

GRASP Taxonomy: A classification system for human hand grasps used in robotics and prosthetics.

Insertion: The point or mode of attachment of a skeletal muscle to the bone or other body part that it moves.

Intermediate Phalanx: The second bone in each finger and toe, located between the proximal and distal phalanges. The thumb and big toe do not have an intermediate phalanx.

International 10-20 Sensor Configuration: A standardized method to place EEG electrodes on the scalp.

JavaOSC: A library for sending and receiving Open Sound Control messages in Java, allowing for communication between software applications.

Kapandji Test: A test to assess the functionality of the hand, particularly the thumb's range of motion and dexterity.

Kinematic Analysis: The study of motion without considering its causes.

Lateral Pinch: A grasp where an object is pinched between the side of the index finger and the thumb.

Lightmyography: An emerging technique that measures muscle activity through the detection of light, offering potential advantages over traditional electromyography.

Matlab: A high-level programming language and environment used for numerical computing, visualization, and programming.

Mental Command: A specific thought pattern recognized by a brain-computer interface to trigger an action or response.

Metacarpal: The five bones that form the middle part of the human hand.

Metacarpophalangeal Joint: The joint between the metacarpal bones and the proximal phalanges of the fingers.

Mirror Neuron System: Neurons that fire both when an individual acts and when the individual observes the same action performed by another.

Mirror Therapy: A therapeutic technique that uses a mirror to create a reflective illusion of an affected limb to trick the brain into thinking movement has occurred without pain.

Motor Cortex: The region of the cerebral cortex involved in the planning, control, and execution of voluntary movements.

Motor Execution: The physical performance of a movement or task.

Motor Imagery: The process of imagining a movement without actually performing it, often used in neurorehabilitation.

Native Schools Act: Legislation passed in New Zealand in 1867 to establish schools that would assimilate Māori children into European ways of thinking and living.

Neural Interface: A technology that allows for communication between the nervous system and external devices.

Neuron: A nerve cell that transmits electrical and chemical signals in the body.

Neurotechnology: Technology that interfaces with the nervous system to monitor or control neural activity.

Opposition Type: The way in which fingers move to meet the thumb, important in grasp classification.

Opposition: The movement that involves grasping of an object between the thumb and fingers.

Palmar Pinch: A precise grasp using the fingertips and thumb, typically used for small objects.

Peripheral Nervous System: The part of the nervous system that consists of the nerves and ganglia outside of the brain and spinal cord.

Phalanges: The bones that form the fingers and toes. Each finger and toe has three phalanges (proximal, intermediate, and distal), except for the thumb and big toe, which have two.

Phalanx: A bone of the finger or toe.

Phantom Pain: Pain that feels like it's coming from a body part that's no longer there.

Polylactic Acid: A biodegradable and bioactive thermoplastic aliphatic polyester derived from renewable resources.

Power Grasp: A type of hand grasp used for holding and manipulating large objects, involving most of the fingers and the palm.

Proximal Interphalangeal Joint: The joint between the proximal and intermediate phalanges of the fingers and toes.

Proximal Phalanx: The first bone in each finger and toe, located closest to the hand or foot.

Radial: Pertaining to the radius bone or the lateral aspect of the limb.

Range of Motion: The full movement potential of a joint, usually its range of flexion and extension.

Reposition: The return movement of the thumb from opposition back to its anatomical position.

Support Vector Machine: A supervised machine learning model used for classification and regression analysis.

Tendon: A flexible but inelastic cord of strong fibrous collagen tissue attaching a muscle to a bone.

Tendon-driven: Powered or moved by tendons (in prosthetics, often referring to the mechanism that mimics human muscle action).

Tohunga Suppression Act: A law enacted in New Zealand in 1907 aimed at stopping traditional Māori healers, as part of wider efforts to suppress Māori culture.

Tripod Grasp: A three-point pinch involving the thumb, index, and middle fingers, similar to the grip used to hold a pen.

Ulnar/Radial Deviation: Movement of the wrist towards the ulna or radius bone.

Underactuated: A system with fewer actuators than degrees of freedom, requiring some form of passive adaptation to achieve control.

Virtual Finger Assignment: A method of categorizing fingers based on their contribution to a grasp, used in hand function analysis.

G2 Māori Terms

Aotearoa: The Māori name for New Zealand, often translated as "land of the long white cloud."

Atua: Gods or spiritual beings in Māori mythology.

Ha a Koro Ma, a Kuia Ma: The breath of life given by ancestors.

Haematua: Atua of the light in the sky.

Haepuru: Atua of the light emanating from some stars.

Hape: Chief of Tainui iwi, notable for his leadership and clubfoot.

Harakeke: The Māori name for the New Zealand flax plant, used in weaving.

Hauā: Disabled or having a disability.

Hauhake: The harvest or act of harvesting.

Haumia-tiketike: Atua associated with wild or uncultivated food.

Hineahuone: The first woman created by the atua Tāne from earth.

Iwi: Tribe or people, a large grouping of Māori with a common ancestor.

Kaitiaki o te Wairoro: Guardian of the brain

Kāpō: Blindness or a blind person.

Kurawaka: A term that refers to the red clay Tāne used to create Hineahuone, often symbolizing the womb or earth from which life is born.

Mahara: Memory or to remember.

Mana: Prestige, authority, or spiritual power.

Mana Ake: Unique identity of individuals and family

Manawa ora: Breath of life.

Mātauranga Māori: Māori knowledge or education system, encompassing history, culture, and traditional practices.

Maui Tikitiki a Taranga: Māui, a demigod and cultural hero in Māori mythology known for his cleverness and tricks.

Mauri: Life force or essence that exists in all living and inanimate things.

Murirangawhenua: Grandmother of Māui.

Ngāti Toa: A Māori iwi based in the southern North Island and in the northern South Island of New Zealand.

Noa: Common or free from tapu (sacred restrictions), making something safe or removing restrictions.

Pāia: Atua of knowledge, land and human bones.

Papatūānuku: The Earth Mother, who represents the earth in Māori creation narratives.

Pou Kaiāwhā: Represents the cerebral cortex in Te Whare o Oro framework, associated with thinking and processing.

Pou Tāhū: Represents the diencephalon and cerebellum in Te Whare o Oro, associated with balance and control.

Pou Tokomanawa: Represents the limbic system in Te Whare o Oro, the emotional centre of the brain.

Pou Tuarongo: Represents the brainstem in Te Whare o Oro, associated with basic life functions.

Pūrakau: Traditional stories, myths, or legends.

Rangatira: Chief or person of high social status.

Ranginui: The Sky Father, who represents the sky in Māori creation narratives.

Raranga: The art of weaving

Rau: Leaf or leaves, often used in traditional uses and symbolism.

Rehua: Atua of kindness, enjoyment, and entertainment.

Roake: Atua of the stars and light behind Ranginui.

Roiho: Atua of the stars and light in front of Ranginui.

Rongomatane: Atua of peace, cultivated food, and agriculture.

Ruatepupuke: A figure associated with the origins of wood carving in Māori tradition.

Ruaumoko: Atua of earthquakes, volcanoes, and seasons.

Taha Hinengaro: Mental and emotional well-being.

Taha Tinana: Physical well-being.

Taha Wairua: Spiritual well-being.

Taha Whānau: Family and social well-being.

Tainui: A waka (canoe) and its associated iwi.

Tāne: Atua of forests and birds, who created humans.

Tangaroa: Atua of the sea.

Tāngata Whaikaha: People with disabilities.

Taniko: A weaving technique used in decorative borders on Māori garments.

Taonga: Treasures or valued possessions, both tangible and intangible.

Tapu: Sacredness, restriction, a spiritual protection or prohibition.

Tawhiri-matea: Atua of winds and storms.

Te Akaaka-matua: Atua of supplejack and vines.

Te ao Māori: The Māori world(view), encompassing the culture, beliefs, and practices of the Māori people.

Te ao Marama: The world of light, life, and reality, as opposed to the supernatural world.

Te ira atua: The divine essence or godly aspect present in all creation.

Te ira tāngata: The human aspect or essence, distinguishing humans from atua (gods) and other beings.

Te Rangihaeata: Chief of Ngāti Toa Iwi

Te Reo Māori: The Māori language.

Te Tiriti o Waitangi: The Treaty of Waitangi, signed in 1840 between Māori chiefs and the British Crown.

Te Whare o Oro: A Māori model representing the development of the brain and its functions.

Te Whare Tapa Whā: A Māori health model encompassing four dimensions of well-being: physical, mental/emotional, spiritual, and family/social.

Te Wheke: An octopus, symbolizing a holistic model of health and well-being in Māori culture.

Tohu: Signs, symbols, or omens, often interpreted as messages from the spiritual realm.

Tohunga: Experts or priests in traditional Māori society, skilled in rituals, healing, and knowledge.

Tukutuku: Decorative lattice panels found in Māori meeting houses, embodying narratives and symbols.

Tūmatauenga: Atua of war, humans, and cultivated food in Māori mythology.

Wairua: Spirit or soul, an essential aspect of Māori belief about life and the universe.

Wairua Theory: A conceptual framework in Māori philosophy regarding the nature and role of the spirit in health and well-being.

Waitā: Associated with the ocean and marine conditions.

Whakairo: The art of carving in wood, bone, and stone, highly esteemed in Māori culture.

Whakapapa: Genealogy or lineage, a fundamental principle in Māori identity and social structure.

Whakarite: Preparation, arrangement, or ceremony, often in a ritual context.

Whakataukī: Proverbs or sayings, encapsulating wisdom, principles, and values of Māori culture.

Whānau Hauā: Families with disabilities, emphasizing the collective aspect of care and support.

Whanaungatanga: Kinship, relationships, and a sense of belonging, a key value in Māori society.

Wharenui: Meeting house in a marae (sacred communal space), representing a tribe's ancestors and hosting gatherings.

Whatukura: Celestial beings in Māori mythology, often associated with guardianship and guidance.

Whatumanawa: The open and healthy expression of emotion

Whenu: Threads in weaving, symbolizing connections and relationships in Māori metaphorical language.

Whenua: Land or country, deeply connected to identity, belonging, and well-being in Māori culture.

G3 Abbreviations

AO: Action Observation

AP: Action Potential

AR: Augmented Reality

BCI: Brain-Computer Interface

CMC: Carpometacarpal joint

CNS: Central Nervous System

DH: Denavit-Hartenberg

DIP: Distal Interphalangeal joint

DoF: Degrees of Freedom

DT: Digital Twin

EEG: Electroencephalography

EMG: Electromyography

FDM: Fused Deposition Modelling

L.Pinch: Lateral Pinch

LMG: Lightmyography

MCP: Metacarpophalangeal joint

ME: Motor Execution

OSC: Open Sound Cloud

P.Pinch: Palmar Pinch

PIP: Proximal Interphalangeal joint

PLA: Polylactic Acid

PNS: Peripheral Nervous System

RoM: Range of Motion

SVM: Support Vector Machine

TBI: Traumatic Brain Injury

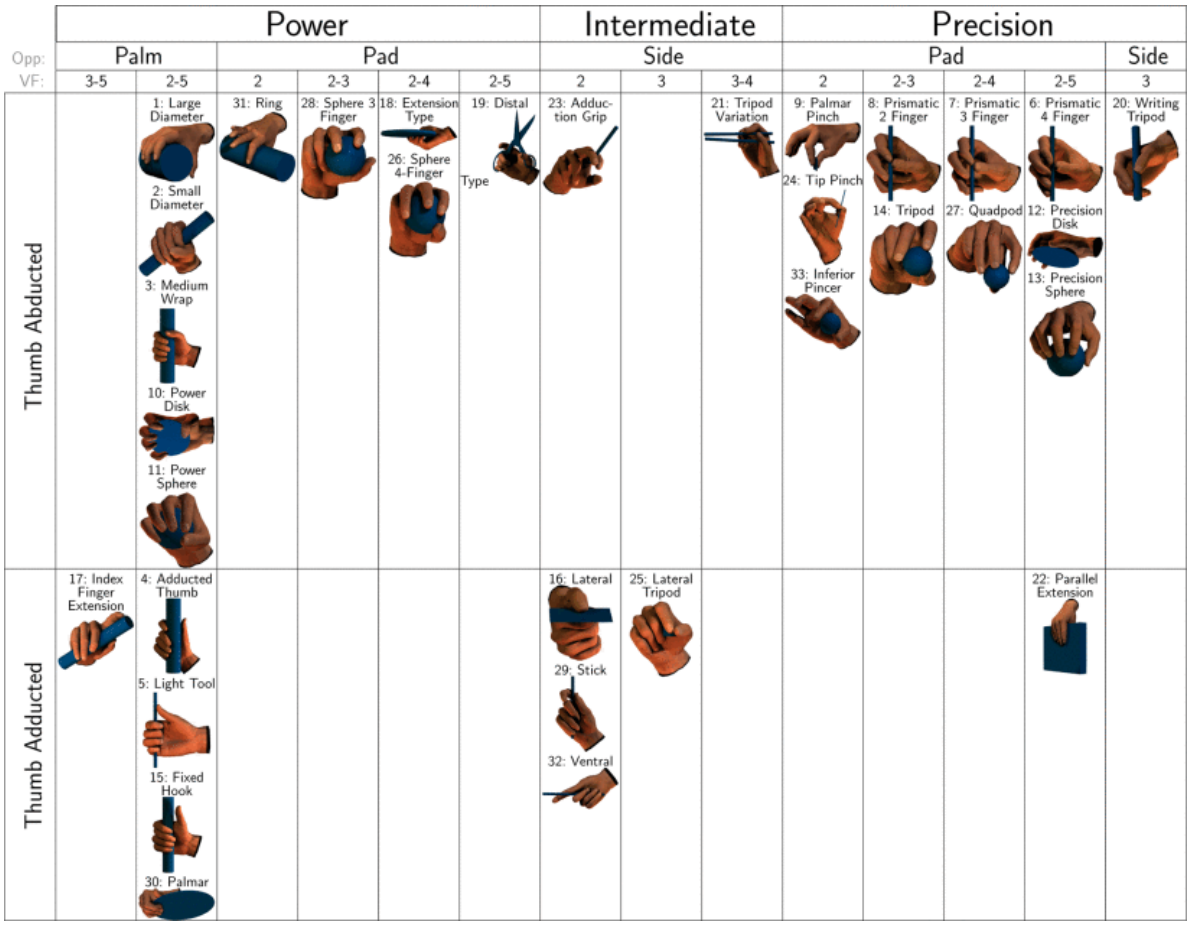
VR: Virtual Reality

Appendix

The following appendix holds information pertaining to the thesis as a whole. In total there are seven appendices that address GRASP Taxonomy, DoF Tables, Kinematic calculations, Prosthesis control code, Digital twin information, controls testing code and tabulated control test results.

Appendix 1: GRASP Taxonomy

Below is a figure detailing the classification of all 33 grasps of the GRASP Taxonomy developed by Feix et al [18].



Appendix 2: DoF Tables

Table of Index DoF

	PIP Joint	DIP Joint	MCP Joint		
	Flexion-extension	Flexion-extension	Flexion-extension	ulnar/radial deviation	Total
Human Hand	1	1	1	1	4
First Hand	1	1	1	0	3
Tuarua	1	1	1	0	3
Dre Hand	1	0	1	0	2
Jerry Hand	1	0	1	0	2

Table of Middle DoF

	PIP Joint	DIP Joint	MCP Joint		
	Flexion-extension	Flexion-extension	Flexion-extension	ulnar/radial deviation	Total
Human Hand	1	1	1	1	4
First Hand	1	1	1	0	3
Tuarua	1	1	1	0	3
Dre Hand	1	0	1	0	2
Jerry Hand	1	0	1	0	2

Table of ring DoF

	PIP Joint	DIP Joint	MCP Joint		
	Flexion-extension	Flexion-extension	Flexion-extension	ulnar/radial deviation	Total
Human Hand	1	1	1	1	4
First Hand	1	1	1	0	3
Tuarua	1	1	1	0	3
Dre Hand	1	0	1	0	2
Jerry Hand	1	0	1	0	2

Table of little DoF

	PIP Joint	DIP Joint	MCP Joint		
	Flexion-extension	Flexion-extension	Flexion-extension	ulnar/radial deviation	Total
Human Hand	1	1	1	1	4
First Hand	1	1	1	0	3
Tuarua	1	1	1	0	3
Dre Hand	1	0	1	0	2
Jerry Hand	1	0	1	0	2

Table of thumb DoF

	IP Joint	MCP Joint		CMC joint			
	Flexion-extension	Flexion-extension	ulnar/radial deviation	Flexion-extension	abduction-adduction	Axial rotation	Total
Human Hand	1	1	1	1	1	1	6
First Hand	1	1	1	1	0	0	4
Tuarua	1	1	1	1	0	0	4
Dre Hand	1	1	0	0	1	0	3
Jerry Hand	1	1	0	0	1	0	3

Appendix 3 Kinematic Calculations

A3. 1 Finger Section Lengths for Kinematic Calculations

A3.1.1 Table of dimensions First Hand

	L1	L2	L3
Index	33.9	25.9	24
Middle	36.1	29.9	24.1
Ring	25.9	24.9	23.9
Little	19.9	20.9	23.9

A3.1.2 Table of dimensions Tuarua

	L1	L2	L3
Index	24	24	26.5
Middle	26	26	28
Ring	24	24	25.5
Little	19	19	21

A3.1.3 Table of dimensions Dre Hand

	L1	L2
Index	42.5	58.5
Middle	42.5	53
Ring	42.5	58.5
Little	42.5	45.5

A3.1.4 Table of dimensions Jerry Hand

	L1	L2
Index	40	49
Middle	40	45
Ring	40	49
Little	36	33

A3.2 Finger Spatial Arrangement for 3D Kinematic Calculations

A3.2.1 Table of Finger Spatial Arrangement (mm)

	Little Finger	Ring Finger	Middle Finger	Index Finger
First Hand	0	21	40.5	58
Tuarua	0	23	46	70
Dre Hand	0	20.9	41.5	62.5
Jerry Hand	0	20.9	41.5	62.5

A3.3 Code for Calculating 2D Kinematics of 3 Link Chain.

The following MATLAB code was used to calculate the RoM of the “First” and “Tuarua” hands fingers.

```
clear
clc
close all

% Define sets of link lengths for four different configurations
linkLengths = [
%First Hand Values
    33.9, 25.9, 24;    % Index
    36.1, 29.9, 24.1;  % Middle
    25.9, 24.9, 23.9;  % Ring
    19.9, 20.9, 23.9   % Little

%Tuarua Values
%       24,24,26.5;   %Index
%       26,26,28;     %Middle
%       24,24,25.5;   %Ring
%       19,19,21;     %Little
];


% Define a list of colors for the perimeter lines
lineColors = ['r', 'g', 'b', 'm']; % Example colors: red, green, blue,
magenta

% Define titles for each plot
plotTitles = {
    'First Hand: Index Finger Trajectory',
    'First Hand: Middle Finger Trajectory',
    'First Hand: Ring Finger Trajectory',
    'First Hand: Little Finger Trajectory'
};

% Loop through each configuration
for config = 1:size(linkLengths, 1)
    % Extract link lengths for the current configuration
    a1 = linkLengths(config, 1);
    a2 = linkLengths(config, 2);
    a3 = linkLengths(config, 3);

    % Initialize vectors to store end-effector positions
    X = [];
    Y = [];

    % Loop through all possible joint angles
    for theta1 = 0:1:90
        for theta2 = 0:1:90
            for theta3 = 0:1:90
                % Convert angles from degrees to radians
                theta1_rad = deg2rad(theta1);
                theta2_rad = deg2rad(theta2);
                theta3_rad = deg2rad(theta3);
```

```
                % Compute the transformation matrix for each link using DH
parameters
                T1 = dh_transform(a1, 0, 0, theta1_rad);
                T2 = dh_transform(a2, 0, 0, theta2_rad);
                T3 = dh_transform(a3, 0, 0, theta3_rad);

                % Compute the overall transformation matrix
                T = T1 * T2 * T3;

                % Extract the end-effector position
                X = [X, T(1,4)];
                Y = [Y, T(2,4)];
            end
        end
    end

    % Adjust the shrink factor to capture concavities. Experiment with this
value.
    shrinkFactor =1; % Example value, adjust as needed to capture
concavities

    % Use the boundary function with a custom shrink factor
    [B,~] = boundary(Y', X', shrinkFactor); % Apply custom shrink factor

    % Plot the workspace for the current configuration with swapped axes
    subplot(2, 2, config); % Arrange plots in a 2x2 grid
    plot(Y(B), X(B), lineColors(config), 'LineWidth', 1); % Use selected
color for the perimeter line
    xlabel('Y Position'); % Swap labels
    ylabel('X Position'); % Swap labels
    axis equal;
    grid on;
    xlim([-20 100]);
    ylim([-60 100]);
end

% Set titles after plotting to keep the loop clean
for i = 1:4
    subplot(2, 2, i);
    title(plotTitles{i});
end

% Function to compute DH transformation matrix
function T = dh_transform(a, alpha, d, theta)
    T = [cos(theta), -sin(theta)*cos(alpha), sin(theta)*sin(alpha),
a*cos(theta);
         sin(theta), cos(theta)*cos(alpha), -cos(theta)*sin(alpha),
a*sin(theta);
         0, sin(alpha), cos(alpha), d;
         0, 0, 0, 1];
end
```

A3.4 Code for Calculating 2D Kinematics of 2 Link Chain.

The following MATLAB code was used to calculate the RoM of the “Jerry” hands fingers.

```
clear;
clc;
close all;

% Define sets of link lengths for four different configurations for a 2-
link chain
linkLengths = [
    % Jerry Hand Values for a 2-link chain
      40,49;   % Index
      40,54;     % Middle
      40,49;   % Ring
      40,33;     % Little
];

% Define a list of colors for the perimeter lines
lineColors = ['r', 'g', 'b', 'm']; % Example colors: red, green, blue,
magenta

% Define titles for each plot
plotTitles = {
    'Jerry Hand: Index Finger Trajectory',
    'Jerry Hand: Middle Finger Trajectory',
    'Jerry Hand: Ring Finger Trajectory',
    'Jerry Hand: Little Finger Trajectory'
};



% Loop through each configuration
for config = 1:size(linkLengths, 1)
    % Extract link lengths for the current configuration
    a1 = linkLengths(config, 1);
    a2 = linkLengths(config, 2);

    % Initialize vectors to store end-effector positions
    X = [];
    Y = [];

    % Loop through all possible joint angles
    for theta1 = 0:1:90
        for theta2 = 0:1:90
            % Convert angles from degrees to radians
            theta1_rad = deg2rad(theta1);
            theta2_rad = deg2rad(theta2);

            % Compute the transformation matrix for each link using DH
parameters
            T1 = dh_transform(a1, 0, 0, theta1_rad);
            T2 = dh_transform(a2, 0, 0, theta2_rad);

            % Compute the overall transformation matrix
            T = T1 * T2;
```

```
            % Extract the end-effector position
            X = [X, T(1,4)];
            Y = [Y, T(2,4)];
        end
    end

    % Adjust the shrink factor to better capture concavities
    shrinkFactor = 1; % Lowered to better capture concavities

    % Use the boundary function with the adjusted shrink factor
    [B,~] = boundary(Y', X', shrinkFactor); % Apply adjusted shrink factor

    % Plot the workspace for the current configuration with swapped axes
    subplot(2, 2, config); % Arrange plots in a 2x2 grid
    plot(Y(B), X(B), lineColors(config), 'LineWidth', 1); % Use selected
color for the perimeter line
    xlabel('Y Position'); % Swap labels
    ylabel('X Position'); % Swap labels
    axis equal;
    grid on;
    xlim([-20 100]);
    ylim([-60 100]);
    title(plotTitles{config}); % Set title for each subplot
end

% Function to compute DH transformation matrix remains unchanged
function T = dh_transform(a, alpha, d, theta)
    T = [cos(theta), -sin(theta)*cos(alpha), sin(theta)*sin(alpha),
a*cos(theta);
         sin(theta), cos(theta)*cos(alpha), -cos(theta)*sin(alpha),
a*sin(theta);
         0, sin(alpha), cos(alpha), d;
         0, 0, 0, 1];
end
```

A3.5 Code for Calculating 2D Kinematics of Coupled 2 Link Chain.

The following MATLAB code was used to calculate the RoM of the “Dre” hand fingers.

```
clear
clc
close all

% Define sets of link lengths for four different manipulator configurations
linkLengths = [
    42.5, 58.5; % Configuration 1
    42.5, 53; % Configuration 2
    42.5, 58.5; % Configuration 3
    42.5, 45.5 % Configuration 4
];
% Define a list of colors for the perimeter lines
lineColors = ['r', 'g', 'b', 'm']; % Example colors: red, green, blue,
magenta

% Define titles for each plot
plotTitles = {
    'Dre Hand: Index Finger Trajectory',
    'Dre Hand: Middle Finger Trajectory',
    'Dre Hand: Ring Finger Trajectory',
    'Dre Hand: Little Finger Trajectory'
};

% Number of configurations
numConfigs = size(linkLengths, 1);

% Create figure
figure;

% Loop through each configuration
for config = 1:numConfigs
    % Extract link lengths for the current configuration
    a1 = linkLengths(config, 1);
    a2 = linkLengths(config, 2);

    % Initialize arrays to store end-effector positions
    X = [];
    Y = [];

    % Loop through the range of theta1
    for theta1_deg = 0:2:90
        theta1 = deg2rad(theta1_deg); % Convert theta1 to radians
        theta2 = 2 * theta1; % Coupling relationship: theta2 is twice
theta1

        % Calculate the position of the end-effector using forward
kinematics
        x = a1*cos(theta1) + a2*cos(theta1 + theta2);
        y = a1*sin(theta1) + a2*sin(theta1 + theta2);

        % Store the positions
        X = [X, x];
        Y = [Y, y];
```

```
    end

    % Plot the range of motion for the current configuration
    subplot(2, 2, config);
    plot(Y, X,  lineColors(config), 'LineWidth', 1);
    xlabel('Y Position');
    ylabel('X Position');
    axis equal;
    grid on;
    xlim([-20 100]);
    ylim([-60 120]);
end
for i = 1:4
    subplot(2, 2, i);
    title(plotTitles{i});
end
```

A3.6 Code for Calculating 3D Kinematics of 3 Link Chain

The following MATLAB code was used to calculate the 3D RoM of the “First” and “Tuarua” hands fingers in relation to each other.

```
clear;
clc;
close all;

% Define sets of link lengths for four different configurations
linkLengths = [
%First Hand Values
    33.9, 25.9, 24;    % Index
    36.1, 29.9, 24.1;  % Middle
    25.9, 24.9, 23.9;  % Ring
    19.9, 20.9, 23.9   % Little
% Tuarua Values
%       24,24,26.5;   %Index
%       26,26,28;     %Middle
%       24,24,25.5;   %Ring
%       19,19,21;     %Little

];

% Define a list of colors for the perimeter lines
lineColors = ['r', 'g', 'b', 'm']; % Example colors: red, green, blue,
magenta

% Define Z values for each configuration (used for the Z-axis as "Z
Position")

zValues = [58, 40.5 ,21 , 0]; % First Hand
% zValues = [70, 46 ,23 , 0];  % Tuarua

% Create a new figure for the 3D plot
figure;
hold on; % Enable holding multiple plots

% Loop through each configuration to plot in 3D
for config = 1:size(linkLengths, 1)
    % Extract link lengths for the current configuration
    a1 = linkLengths(config, 1);
    a2 = linkLengths(config, 2);
    a3 = linkLengths(config, 3);

    % Initialize vectors to store end-effector positions
    X = [];
    Y = [];

    % Loop through all possible joint angles
    for theta1 = 0:5:90
        for theta2 = 0:5:90
            for theta3 = 0:5:90
                % Convert angles from degrees to radians
                theta1_rad = deg2rad(theta1);
                theta2_rad = deg2rad(theta2);
```

```
                theta3_rad = deg2rad(theta3);

                % Compute the transformation matrix for each link using DH
parameters
                T = dh_transform(a1, 0, 0, theta1_rad) * ...
                    dh_transform(a2, 0, 0, theta2_rad) * ...
                    dh_transform(a3, 0, 0, theta3_rad);

                % Extract the end-effector position
                X = [X, T(1,4)];
                Y = [Y, T(2,4)];
            end
        end
    end

    % Adjust the shrink factor to capture concavities.
    shrinkFactor = 1; % Use the same shrink factor as before

    % Use the boundary function with the custom shrink factor
    [B,~] = boundary(Y', X', shrinkFactor); % Apply custom shrink factor,
swapping X and Y

    % Use the specified Z value for the configuration height
    ZPlot = ones(size(Y(B))) * zValues(config);

    % Plot the 3D boundary for the current configuration with adjusted axes
    plot3(ZPlot, -Y(B), X(B), 'Color', lineColors(config), 'LineWidth',
1); % Swapping X and Y, using Z for height
end

% Set the 3D plot appearance
xlabel('Z Position'); % Now represents the original Y data, swapped
ylabel('X Position'); % Now represents the original X data, swapped
zlabel('Y Position'); % Configuration height labeled as "Z Position"
title('First Hand 3D Plot of Finger Trajectories');
grid on;
axis equal;
view(3); % Adjust the view to better visualize the 3D aspect


% After plotting all the configurations

% Define the start and end Z positions based on your zValues array
xStart = min(zValues);
xEnd = max(zValues) + 20; % Adding a buffer to ensure visibility beyond the
last configuration

% Y position for the line
yLinePos = 0;

% X position for the line, set to 0 to run through x = 0 on the XY plane
zLinePos = 0;

% Plot a line through x = 0 on the XY plane, extending through the entire Z
range used
plot3([xStart, xEnd], [yLinePos, yLinePos], [zLinePos, zLinePos], 'k--',
'LineWidth', 0.5);
```

```
legend("Index","Middle", "Ring", "Little", "Palm");

% Function to compute DH transformation matrix remains the same
function T = dh_transform(a, alpha, d, theta)
    T = [cos(theta), -sin(theta)*cos(alpha), sin(theta)*sin(alpha),
a*cos(theta);
         sin(theta), cos(theta)*cos(alpha), -cos(theta)*sin(alpha),
a*sin(theta);
         0, sin(alpha), cos(alpha), d;
         0, 0, 0, 1];
end
```

A3.7 Code for Calculating 3D Kinematics of 2 Link Chain

The following MATLAB code was used to calculate the 3D RoM of the “Jerry” hands fingers in relation to each other.

```
clear;
clc;
close all;

% Define sets of link lengths for two different configurations (2-link
chain)
linkLengths = [
    % Jerry Hand Values for a 2-link chain
      40,49;    % Index
      40,54;      % Middle
      40,49;    % Ring
      40,33;      % Little
];

% Define a list of colors for the perimeter lines
lineColors = ['r', 'g', 'b', 'm']; % Example colors: red, green, blue,
magenta

% Define Z values for each configuration (used for the Z-axis as "Z
Position")
zValues = [63.5, 41.5 ,20.9 , 0];  % Tuarua

% Create a new figure for the 3D plot
figure;
hold on; % Enable holding multiple plots

% Loop through each configuration to plot in 3D
for config = 1:size(linkLengths, 1)
    % Extract link lengths for the current configuration
    a1 = linkLengths(config, 1);
    a2 = linkLengths(config, 2);

    % Initialize vectors to store end-effector positions
    X = [];
    Y = [];

    % Loop through all possible joint angles
    for theta1 = 0:1:90
        for theta2 = 0:1:90
            % Convert angles from degrees to radians
            theta1_rad = deg2rad(theta1);
            theta2_rad = deg2rad(theta2);

            % Compute the transformation matrix for each link using DH
parameters
            T = dh_transform(a1, 0, 0, theta1_rad) * ...
                dh_transform(a2, 0, 0, theta2_rad);

            % Extract the end-effector position
            X = [X, T(1,4)];
            Y = [Y, T(2,4)];
        end
```

```
    end

    % Adjust the shrink factor to capture concavities.
    shrinkFactor = 1; % Use the same shrink factor as before

    % Use the boundary function with the custom shrink factor
    [B,~] = boundary(Y', X', shrinkFactor); % Apply custom shrink factor,
swapping X and Y

    % Use the specified Z value for the configuration height
    ZPlot = ones(size(Y(B))) * zValues(config);

    % Plot the 3D boundary for the current configuration with adjusted axes
    plot3(ZPlot, -Y(B), X(B), 'Color', lineColors(config), 'LineWidth',
1); % Swapping X and Y, using Z for height
end

% Set the 3D plot appearance
xlabel('Z Position'); % Now represents the original Y data, swapped
ylabel('X Position'); % Now represents the original X data, swapped
zlabel('Y Position'); % Configuration height labeled as "Z Position"
title('Jerry Hand 3D Plot of Finger Trajectories');
grid on;
axis equal;
view(3); % Adjust the view to better visualize the 3D aspect

% Plot a line through x = 0 on the XY plane, extending through the entire Z
range used
xStart = min(zValues);
xEnd = max(zValues) + 20; % Adding a buffer to ensure visibility beyond the
last configuration
yLinePos = 0;
zLinePos = 0;
plot3([xStart, xEnd], [yLinePos, yLinePos], [zLinePos, zLinePos], 'k--',
'LineWidth', 0.5);

legend("Index","Middle", "Ring", "Little", "Palm");

% DH transformation matrix function remains unchanged
function T = dh_transform(a, alpha, d, theta)
    T = [cos(theta), -sin(theta)*cos(alpha), sin(theta)*sin(alpha),
a*cos(theta);
         sin(theta), cos(theta)*cos(alpha), -cos(theta)*sin(alpha),
a*sin(theta);
         0, sin(alpha), cos(alpha), d;
         0, 0, 0, 1];
end
```

A3.8 Code for Calculating 3D Kinematics of Coupled 2 Link Chain

The following MATLAB code was used to calculate the 3D RoM of the “Dre” hands fingers in relation to each other.

```
clear
clc
close all


linkLengths = [
    42.5, 58.5; % Configuration 1
    42.5, 53; % Configuration 2
    42.5, 58.5; % Configuration 3
    42.5, 45.5 % Configuration 4
];
% Define a list of colors for the perimeter lines
lineColors = ['r', 'g', 'b', 'm']; % Example colors: red, green, blue,
magenta

% Define Z-axis offsets for each manipulator configuration
zOffsets = [62.5, 41.5, 20.9, 0];

% Create figure for 3D plotting
figure;
hold on;

% Loop through each configuration
for config = 1:size(linkLengths, 1)
    % Extract link lengths for the current configuration
    a1 = linkLengths(config, 1);
    a2 = linkLengths(config, 2);

    % Initialize arrays to store end-effector positions
    X = [];
    Y = [];
    Z = [];

    % Loop through the range of theta1
    for theta1_deg = 0:5:90
        theta1 = deg2rad(theta1_deg); % Convert theta1 to radians
        theta2 = 2 * theta1; % Coupling relationship: theta2 is twice
theta1

        % Calculate the position of the end-effector using forward
kinematics
        x = a1 * cos(theta1) + a2 * cos(theta1 + theta2);
        y = a1 * sin(theta1) + a2 * sin(theta1 + theta2);

        % Store the positions
        X = [X, x];
        Y = [Y, y];
        % Assign the same Z value (offset) to all points in the current
configuration
        Z = [Z, zOffsets(config) * ones(size(x))];
    end
```

```
    % Plot the range of motion for the current configuration in 3D
    plot3(Z, -Y, X, 'k-', 'Color', lineColors(config), 'LineWidth', 0.5);
end

% Customize the 3D plot
% Set the 3D plot appearance
xlabel('Z Position'); % Now represents the original Y data, swapped
ylabel('X Position'); % Now represents the original X data, swapped
zlabel('Y Position'); % Configuration height labeled as "Z Position"
title('Jerry Hand 3D Plot of Finger Trajectories');
grid on;
axis equal;

view(3); % Adjust the viewing angle for better visualization

% Plot a line through x = 0 on the XY plane, extending through the entire Z
range used
xStart = min(zOffsets);
xEnd = max(zOffsets) + 20; % Adding a buffer to ensure visibility beyond
the last configuration
yLinePos = 0;
zLinePos = 0;
plot3([xStart, xEnd], [yLinePos, yLinePos], [zLinePos, zLinePos], 'k--',
'LineWidth', 0.5);

legend("Index","Middle", "Ring", "Little", "Palm");


hold off;
```

Appendix 4: Prosthesis Control Code

The following Arduino code was used to control the “Jerry” hand by receiving mental command inputs from Emotiv BCI-OSC.

```
#include <SPI.h>

#include <Ethernet.h>

#include <EthernetUdp.h>

#include <OSCBundle.h>

#include <Servo.h>



// you can find this written on the board of some Arduino Ethernets or shields

byte mac[] = {  0xDE, 0xAD, 0xBE, 0xEF, 0xFE, 0xED };

IPAddress ip(255,255,255,255);

Servo PINKY, RING, MIDDLE, INDEX, THUMB1, THUMB2, WRIST;

int serverPort = 8000; // Emotiv BCI out port
float value;


//Create UDP message object

EthernetUDP Udp;



void setup(){
 // disable SD card if one in the slot
  pinMode(4,OUTPUT);
  digitalWrite(4,LOW);
 // start serial monitor
  Serial.begin(9600); //9600 for a "normal" Arduino board (Uno for example).
115200 for a Teensy ++2
  Serial.println("Emotiv BCI OSC test");
 // start the Ethernet connection:
 // NOTE: Alternatively, you can assign a fixed IP to configure your Ethernet
shield.
  Ethernet.begin(mac,ip);
```

```
 // print your local IP address:
  Serial.print("Arduino IP address: ");
  for (byte thisByte = 0; thisByte < 4; thisByte++) {
    // print the value of each byte of the IP address:
    Serial.print(Ethernet.localIP()[thisByte], DEC);
    Serial.print(".");
  }
  Udp.begin(serverPort);
  Serial.println("Connected");

  THUMB1.attach(3);
  pinMode(3, OUTPUT);
  MIDDLE.attach(4);
  pinMode(4, OUTPUT);
  THUMB2.attach(5);
  pinMode(5, OUTPUT);
  WRIST.attach(6);
  pinMode(6, OUTPUT);
  PINKY.attach(7);
  pinMode(7, OUTPUT);
  INDEX.attach(7);
  pinMode(7, OUTPUT);
  RING.attach(8);
  pinMode(8, OUTPUT);







  }

void loop(){
  //process received data from Emotiv BCI
  OSCMsgReceive();
}

void OSCMsgReceive() {
  int size = Udp.parsePacket();
  if(size > 0) {
    OSCBundle bundleIN;
    while(size--)
      bundleIN.fill(Udp.read());
    if(!bundleIN.hasError()){
        bundleIN.route("/com", processMC); // Mental_Commands
    }
  }
}

void processMC(OSCMessage &msg, int addrOffset) {
```

```
  if(msg.match("/neutral", addrOffset)) {
    Serial.print("MC - Neutral: ");
  } else if(msg.match("/push", addrOffset)) {
    Serial.print("MC - Push: ");
  } else if(msg.match("/pull", addrOffset)) {
   Serial.print("MC - Pull: ");
  } else if(msg.match("/left", addrOffset)) {
    Serial.print("MC - Left: ");
  } else if(msg.match("/right", addrOffset)) {
    Serial.print("MC - Right: ");
  } else if(msg.match("/lift", addrOffset)) {
    Serial.print("MC - lift: ");
  } else if(msg.match("/drop", addrOffset)) {
    Serial.print("MC - drop: ");
  } else if(msg.match("/rotateLeft", addrOffset)) {
    Serial.print("MC - rotateLeft: ");
  } else if(msg.match("/rotateRight", addrOffset)) {
    Serial.print("MC - rotateRight: ");
  } else if(msg.match("/rotateClockwise", addrOffset)) {
    Serial.print("MC - rotateClockwise: ");
  } else if(msg.match("/rotateCounterClockwise", addrOffset)) {
    Serial.print("MC - rotateCounterClockwise: ");
  } else if(msg.match("/rotateForwards", addrOffset)) {
    Serial.print("MC - rotateForwards: ");
  } else if(msg.match("/rotateReverse", addrOffset)) {
    Serial.print("MC - rotateReverse: ");
  } else if(msg.match("/disappear", addrOffset)) {
    Serial.print("MC - disappear: ");
  }
  if(msg.isFloat(0)) {
    float value = msg.getFloat(0);
    Serial.println(value);
  }

  if (msg.match("/push", addrOffset))  {

     WRIST.write(140);
   PINKY.write(45);
   RING.write(45);
   INDEX.write(135);
   THUMB2.write(180);

  }
  else {
    relax();
    delay(100);

}
```

```
}

 void relax() {
   WRIST.write(140);
   THUMB1.write(120);
   THUMB2.write(90);
   PINKY.write(0);
   RING.write(0);
   MIDDLE.write(180);
   INDEX.write(180);
}

void fist() {
   WRIST.write(140);
   PINKY.write(45);
   delay(100 );
   RING.write(45);
   delay(100);
   MIDDLE.write(135);
   delay(100);
   INDEX.write(135);
   delay(400);
   THUMB1.write(0);
   THUMB2.write(180);
}
```

Appendix 5: Digital Twin

The following MATLAB code was used as the digital twin for the training of action observation. MATLAB receives a mental command string from Emotiv BCI-OSC and triggers the corresponding grasp animation.

```
function setupOSCListener()
    import com.illposed.osc.*;  % Import JavaOSC packages

    % Define the OSC port and address to listen to
    port = 7400;  % Example port number, replace with actual
    address = '/emotiv';  % Example OSC address, replace with actual

    % Create an OSC port listener
    oscPort = OSCPortIn(port);

    % Define the callback function to handle incoming OSC messages
    % This function will filter messages based on the address and then
parse the command
    oscListener = @(event) handleOSCMessage(event, @playVideoChoice);
    oscPort.addListener(address, oscListener);

    % Start listening for incoming OSC messages
    oscPort.startListening();

    disp('Listening for OSC messages...');
end

function handleOSCMessage(event, playVideoCallback)
    % Extract the OSC message
    message = event.getMessage();
    arguments = message.getArguments();
    mentalCommand = char(arguments.get(0));  % Assuming the command is the
first argument

    disp(['Received command: ', mentalCommand]);

    % Map the received mental command to video choices and play the
corresponding video
    % This assumes your mental command strings match the expected choices
    playVideoCallback(mentalCommand);
end

function playVideoChoice(mentalCommand)
    if strcmp(mentalCommand, 'push')
        filename = 'Ball Grasp.mp4';  % Replace with the actual path to
Video A
    elseif strcmp(mentalCommand, 'pull')
        filename = 'Dog.mp4';  % Replace with the actual path to Video B
    elseif strcmp(mentalCommand, 'left')
        filename = 'Bird.mp4';  % Replace with the actual path to Video B
    elseif strcmp(mentalCommand, 'right')
        filename = 'Palmar Pinch.mp4';  % Replace with the actual path to
Video B
    else
```

```
        disp('Invalid choice. Exiting...');
        return;
    end

    % The rest of the function remains the same as your provided code
    videoObj = VideoReader(filename);  % Open the video file

    figure('Name', 'Video Player');  % Create a figure window for video
display

    while hasFrame(videoObj)  % Iterate through each frame of the video
        frame = readFrame(videoObj);  % Read the current frame

        % Display the frame in the figure window
        imshow(frame);
        drawnow;
    end

    % Close the video file by deleting the video object
    delete(videoObj);
end
```

Appendix 6: Controls Testing Code

The following MATLAB code was used during the testing phase.

```
% Initialize arrays
% eeglab;

timeArray = [];
errorArray = [];

% Start the experiment
input('Press Enter to begin the experiment.');

% Define the gestures and their corresponding labels
gestures = {'fist', 'palmar pinch', 'lateral pinch', 'fist'};
numGestures = length(gestures);

% Define the port number for OSC
osc_port_number = 8050;

% Initialize variables for OSC
osc_library_added = false;
java_classes_imported = false;

% Add the Java OSC library to the MATLAB Java classpath (only once)
if ~exist('osc_library_added', 'var')
    javaaddpath('javaosctomatlab.jar');
    osc_library_added = true;
end

while true
    % Ask the user which run they want to perform
    selectedRun = input('Enter the run number you would like to perform (or
enter 0 to exit): ');

    if selectedRun == 0
        break; % Exit the loop when the user enters 0
    elseif selectedRun < 1 || selectedRun > numGestures
        fprintf('Invalid run number. Please enter a valid run number or 0
to exit.\n');
    else
        % Initialize OSC
        initializeOSC(osc_library_added, java_classes_imported,
osc_port_number);

        % Define the OSC method (address) you want to listen for (wildcard
for /com/)
        osc_method = '/com/push';

        % Start listening for OSC messages on the specified port and method
        startListeningOSC(osc_port_number, osc_method);

        % Get gestures for the selected run
        currentGesture = gestures{selectedRun};

        % PRoMpt the user with the current gesture
```

```
        fprintf('Perform gesture: %s\n', currentGesture);

        while true
            % Countdown
            fprintf('3 ');
            sound(10 * sin(1:4000));  % Beep sound
            pause(1);
            fprintf('2 ');
            sound(10 * sin(1:4000));
            pause(1);
            fprintf('1 ');
            sound(10 * sin(1:4000));
            pause(1);
            fprintf('Go!\n');
            sound(sin(1:8000));

            % Start timer
            tic;

            % PRoMpt user to start performing gesture
            input('Start performing the gesture (press Enter when done).');

            % Calculate elapsed time
            elapsedTime = toc;

            % Check if the gesture was performed correctly
            if elapsedTime > 8
                % Exceeded time
                fprintf('Time exceeded.\n');
                fprintf('-------------------------------------------------
--\n');

                % Append 8 seconds to array
                timeArray = [timeArray, 8];

                % Increment number of incorrect gestures
                errorArray = [errorArray, 1];
            else
                % Correct gesture performed within allocated time
                fprintf('Gesture completed in %f seconds.\n', elapsedTime);
                fprintf('-------------------------------------------------
--\n');

                % Append time to array
                timeArray = [timeArray, elapsedTime];
                break; % Break out of the while loop and proceed to the
next gesture
            end
        end

        % Stop listening for OSC messages
        stopListeningOSC();

        % Display results for the selected run
        fprintf('\n');
        fprintf('-------------------------------------------------------
\n');
        fprintf('Results for Run %d (%s):\n', selectedRun, currentGesture);
        fprintf('Time: %.2f seconds\n', timeArray(end));
```

```
        totalIncorrectGestures = sum(errorArray);
        fprintf('Total number of incorrect gestures: %d\n',
totalIncorrectGestures);
        fprintf('-------------------------------------------------------
\n');

        % PRoMpt user to press Enter to start the next gesture
        if selectedRun < numGestures
            input('Press Enter to start the next gesture.');
        end
    end
end

% Clean up any remaining OSC objects
clear com.illposed.osc.MatlabOSCListener

% Initialize OSC
function initializeOSC(osc_library_added, java_classes_imported,
osc_port_number)
    % Check if the OSC library and classes have been added and imported
    if ~osc_library_added
        % Add the Java OSC library to the MATLAB Java classpath
        javaaddpath('javaosctomatlab.jar');
        osc_library_added = true;
    end

    if ~java_classes_imported
        % Import necessary Java classes
        import com.illposed.osc.*;
        import java.lang.String;
        java_classes_imported = true;
    end

    disp(['OSC initialized for port ' num2str(osc_port_number) '.']);
end

% Start listening for OSC messages
function startListeningOSC(osc_port_number, osc_method)
    % Check if the receiver object already exists in the workspace
    if evalin('base', 'exist(''osc_receiver'', ''var'')')
        disp('OSC is already listening.');
        return;
    end

    % Create an OSC receiver on the specified port
    receiver = OSCPortIn(osc_port_number);

    % Create a MATLAB OSC listener
    osc_listener = MatlabOSCListener();

    % Add the listener to the receiver for the specified method
    receiver.addListener(osc_method, osc_listener);

    % Start listening for OSC messages
    receiver.startListening();

    % Store the receiver and listener objects in the workspace
    assignin('base', 'osc_receiver', receiver);
    assignin('base', 'osc_listener', osc_listener);
```

```
    disp(['Listening for OSC messages on port ' num2str(osc_port_number) '
with method ' osc_method '...']);
end

% Stop listening for OSC messages
function stopListeningOSC()
    % Check if the receiver object exists in the workspace
    if evalin('base', 'exist(''osc_receiver'', ''var'')')
        % Retrieve the receiver object from the workspace
        receiver = evalin('base', 'osc_receiver');

        % Stop listening for OSC messages and clear the receiver object
        try
            receiver.stopListening();
        catch
            % Handle any exceptions if they occur while stopping the
receiver
        end
        clear receiver;

        disp('Stopped listening for OSC messages.');
    else
        disp('No OSC receiver is active.');
    end

    % Clear any existing objects of MatlabOSCListener class
    clear com.illposed.osc.MatlabOSCListener
end

% Function to get gestures for each run
function gestures = run1Gestures()
    gestures = {'Fist', 'Fist', 'Fist', 'Fist', 'Fist', 'Fist', 'Fist',
'Fist'};
end

function gestures = run2Gestures()
    gestures = {'Palmar Pinch', 'Palmar Pinch','Palmar Pinch','Palmar
Pinch',...
        'Palmar Pinch','Palmar Pinch','Palmar Pinch','Palmar Pinch',};
end

function gestures = run3Gestures()
    gestures = {'Tripod Pinch', 'Tripod Pinch', 'Tripod Pinch', 'Tripod
Pinch',...
        'Tripod Pinch', 'Tripod Pinch', 'Tripod Pinch', 'Tripod Pinch',};
end

function gestures = run4Gestures()
    gestures = {'Lateral Pinch', 'Lateral Pinch', 'Lateral Pinch', 'Lateral
Pinch', ...
        'Lateral Pinch', 'Lateral Pinch', 'Lateral Pinch', 'Lateral
Pinch', };
end

function gestures = run5Gestures()
    gestures = {'Fist', 'Palmar Pinch', 'Fist', 'Palmar Pinch',...
        'Fist', 'Palmar Pinch', 'Fist', 'Palmar Pinch'};
end
```

```
function gestures = run6Gestures()
    gestures = {'Fist', 'Palmar Pinch', 'Lateral Pinch', 'Fist', ...
        'Palmar Pinch', 'Lateral Pinch', 'Fist', 'Palmar Pinch'};
end

function gestures = run7Gestures()
    gestures = {'Fist', 'Palmar Pinch', 'Lateral Pinch', 'Tripod Pinch',...
        'Fist', 'Palmar Pinch', 'Lateral Pinch', 'Tripod Pinch'};
end

function formattedStr = formatDatetimeWithMilliseconds(dt)
    formattedStr = sprintf('%04d-%02d-%02d %02d:%02d:%02d.%03d', ...
        year(dt), month(dt), day(dt), hour(dt), minute(dt), second(dt),
millisecond(dt));
end
```

Appendix 7: Controls Test Results Tabulated

A7.1 Motor Execution Test Results - Single Grasp

ME Testing - Fist								Average	Anticipated	Overtime	Exlusive Average
0.008612	1.783423	7.4	0.3384	0.069457	1.31737	5.95095	1.95	2.352277	2	0	3.123357167
0.005171	0.109108	8	8	7.779918	2.960475	3.003958	0.66	3.814829	2	2	3.60108775
8	8	1.782091	0.282371	4.853796	3.790031	0.772953	1.34	3.602655	0	2	2.136873667
0.005101	0.225142	5.702076	4.513714	8	8	0.6103	3.47	3.815792	1	2	2.9042464
4.75258	8	7.28	8	1.088157	0.570049	0.621313	4.41	4.340262	0	2	3.120349833
ME Testing - Palmar Pinch								**Average**	**Anticipated**	**Overtime**	**Exlusive Average**
6.69304	1.76836	1.000112	5.010025	4.956298	3.092163	2.525708	0.0244	3.133763	1	0	3.577958
2.579586	1.160332	1.955143	4.503492	1.541227	2.907474	3.335194	3.01	2.624056	0	0	2.624056
3.4468	3.363364	5.480616	4.05994	2.732122	2.33536	4.586093	1.3	3.413037	0	0	3.413036875
3.84508	0.638656	1.095849	1.959218	2.859213	3.580875	3.887061	3.28	2.643244	0	0	2.64324395
5.033893	3.61298	2.690426	2.416741	1.774851	2.844032	3.836928	3.73	3.242481	0	0	3.242481375

ME Testing - Lateral Pinch								Average	Anticipated	Overtime	Exlusive Average
6.45952	7.16873	2.54403	0.88042	1.82348	3.41686	6.54412	6.88584	4.465375	0	0	4.465375
0.05562	4.08598	3.33929	1.77686	0.95892	2.70092	7.54328	2.58562	2.880811	0	0	2.88081125
4.15032	5.62415	0.8945	7.77426	0.00456	2.01426	3.97799	2.40703	3.355884	1	0	3.834644286
2.27872	0.2951	4.87651	4.02143	0.41183	2.22917	7.26613	1.9165	2.911924	0	0	2.91192375
1.15916	3.91562	0.009978	1.93644	5.37708	6.09296	1.9011	5.82573	3.277259	0	0	3.744012857
ME Testing - Tripod								**Average**	**Anticipated**	**Overtime**	**Exlusive Average**
6.90483	4.98639	2.64718	0.50847	2.48786	2.60147	5.83685	5.10046	3.884189	0	0	3.88418875
7.0977	3.77772	0.95675	5.70596	6.08628	4.49022	2.16774	3.95036	4.279091	0	0	4.27909125
4.18186	3.42033	0.00345	0.86313	0.25143	5.09128	2.51485	4.06857	2.549363	1	0	2.913064286
7.26053	1.99434	3.28306	6.04441	1.83039	0.61584	2.31801	1.28977	3.079544	0	0	3.07954375
8	3.46496	5.06723	0.4553	6.42938	0.003454	4.14047	4.31474	3.984442	1	1	3.97868

A7.2 Motor Execution Test Results – Multi-Grasp

ME Testing - Fist + P.Pinch								Average	Anticipated	Overtime	Exlusive Average
8	8	8	8	5.702076	8	7.736322	2.97	7.05105	0	5	5.469466
8	2.685769	1.457695	3.166812	8	8	1.1	8	5.051285	0	4	2.102569
8	5.419254	6.47968	8	8	0.1137	8	3.36	5.921579	1	4	5.086311333
8	8	0.136	8	8	3.81469	1.651116	8	5.700226	1	5	2.732903
0.0048	6.48893	8	8	0.004576	8	8	3.8619	5.295026	2	4	5.175415
ME Testing - Fist + P.Pinch + L.Pinch								**Average**	**Anticipated**	**Overtime**	**Exlusive Average**
8	8	8	8	8	8	8	8	8	0	8	0
2.78	8	8	8	8	8	3.98	8	6.845	0	6	3.38
8	8	7.845	8	8	8	8	8	7.980625	0	7	7.845
8	8	8	8	8	8	8	8	8	0	8	0
8	8	8	8	8	8	8	8	8	0	8	0
ME Training - Fist + P.Pinch + L.Pinch + Tripod								**Average**	**Anticipated**	**Overtime**	**Exlusive Average**
8	8	8	8	8	6.645	8	8	7.830625	0	7	6.645
8	8	8	8	8	8	8	8	8	0	8	0
8	8	8	8	8	8	8	8	8	0	8	0
8	8	8	8	8	8	8	8	8	0	8	0
8	8	8	8	8	8	8	8	8	0	8	0

A7.3 Action Observation Test Results – Single Grasp

DT Testing - Fist								Average	Anticipated	Overtime	Exclusive Average
3.615964	4.634377	8	6.262731	2.547611	5.415916	8	2.918091	5.174336	0	2	4.232448333
2.356981	4.474943	4.808628	2.263866	4.171563	3.072014	4.68391	2.871308	3.587902	0	0	3.587901625
4.860108	3.688927	0.0234	2.729452	3.513103	2.636876	5.760073	5.577759	3.598712	1	0	4.109471143
3.19308	4.740934	5.346308	4.33752	8	3.131128	2.558446	5.654286	4.620213	0	1	4.137386
0.00345	4.637446	3.50526	3.544453	4.994924	5.653879	8	8	4.792427	1	2	4.4671924

DT Testing - Palmar Pinch								Average	Anticipated	Overtime	Exclusive Average
3.28724	4.21307	4.21735	3.87521	2.31601	4.92356	3.12273	2.65281	3.575998	0	0	3.5759975
2.14271	4.06813	4.37148	2.05806	0.00432	0.00346	4.2581	2.61028	2.439568	2	0	3.25146
8	3.35357	2.27855	2.48132	3.19373	2.39716	5.23643	5.07069	4.001431	0	1	3.430207143
2.9028	4.30994	4.86028	3.9432	3.85378	2.84648	2.32586	5.14026	3.772825	0	0	3.772825
5.15146	4.21586	3.1866	8	4.54084	0.00477	5.1048	4.72956	4.366736	0	1	3.847698571

DT Testing - Lateral Pinch								Average	Anticipated	Overtime	Exclusive Average
3.28724	0.00325	4.21735	3.87521	2.31601	4.92356	3.12273	2.65281	3.04977	1	0	3.484987143
2.14271	0.00459	4.37148	2.05806	3.79233	8	0.00436	2.61028	2.872976	2	1	2.994972
4.41828	3.35357	5.27855	2.48132	3.19373	5.39716	5.23643	5.07069	4.303716	0	0	4.30371625
2.9028	4.30994	0.034	8	3.85378	2.84648	2.32586	5.14026	3.67664	1	1	3.563186667
5.15146	4.21586	3.1866	3.22223	4.54084	8	5.1048	4.72956	4.768919	0	1	4.307335714

DT Testing - Tripod								Average	Anticipated	Overtime	Exclusive Average
3.28724	4.21307	4.21735	3.87521	2.31601	4.92356	8	2.65281	4.185656	0	1	3.64075
2.14271	0.0797	0.00349	2.05806	3.79233	2.79274	4.2581	2.61028	2.217176	2	0	2.94237
4.41828	3.35357	5.27855	8	3.19373	2.39716	5.23643	5.07069	4.618551	0	1	4.135487143
2.9028	4.30994	4.86028	3.9432	3.85378	2.84648	2.32586	5.14026	3.772825	0	0	3.772825
5.15146	4.21586	0.05689	3.22223	4.54084	5.13989	5.1048	8	4.428996	1	1	4.562513333

A7.4 Action Observation Test Results – Multi-Grasp

DT Testing - Fist + P.Pinch								Average	Anticipated	Overtime	Exclusive Average
8	8	8	4.6242	2.9168	8	8	8	6.942625	0	5	3.7705
8	8	8	5.4136	8	3.2026	4.4209	8	6.629638	0	4	4.3457
2.3698	8	8	8	8	8	2.0625	8	6.554038	0	4	2.21615
4.4967	8	8	3.6212	8	8	3.5256	8	6.455438	0	5	3.881166667
8	4.6163	8	2.6666	8	8	8	8	6.910363	0	6	3.64145

DT Testing - Fist + P.Pinch + L.Pinch								Average	Anticipated	Overtime	Exclusive Average
8	8	7.4062	8	8	8	8	8	7.925775	0	7	7.4062
8	8	8	8	8	8	8	8	8	0	8	8
8	8	8	8	8	8	8	8	8	0	8	8
8	8	8	8	8	8	8	8	8	0	8	8
8	8	8	8	8	8	8	8	8	0	8	8

DT Testing - Fist + P.Pinch + L.Pinch + Tripod								Average	Anticipated	Overtime	Exclusive Average
8	8	8	8	8	8	8	8	8	0	8	0
8	8	8	8	8	8	8	8	8	0	8	0
8	8	8	8	8	8	8	8	8	0	8	0
8	8	8	8	8	8	8	8	8	0	8	0
8	8	8	8	8	8	8	8	8	0	8	0