The Design and Development of an Electromechanical Adaptation for a Novel 3D Printed Functional Hand Prosthesis

MINOR DISSERTATION

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DECLARATION

I, *Moegammad Ameen Bardien*, hereby declare that the work on which this dissertation/thesis is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university.

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Abstract

Globally an estimated 22.3 million people live with upper-limb amputations. To mitigate the effects of upper-limb loss on completing activities of daily living (ADLs), amputees are prescribed upper-limb prostheses. In lower to middle-income countries (LMICs), upper-limb amputees are generally limited to the use of body-driven prostheses. Yet users of body-driven prostheses often abandon their prostheses due to the overexertion of their shoulder and a lack of features that amputees find useful for completing ADLs such as wrist pronation and supination. The aim of this study was thus to design an electromechanical hand prosthesis that meets the functional and grasping requirements of prosthesis users.

To this end, the Self-Actuated Tenim Hand (SATH), a functional electromechanically actuated prosthesis, was developed. The SATH, based on the novel body-driven Tenim Hand, incorporated design refinements that improved on its predecessor's grasping capabilities. An electromechanical actuator and a wrist supination and pronation mechanism were integrated into the SATH thereby improving its functional capabilities. The actuator is controlled by a simple yet robust trigger mechanism that allows the user to induce flexion or extension of the hand.

The Anthropomorphic Hand Assessment Protocol (AHAP) was used as a design validation tool to assess the functional capabilities of the SATH. AHAP measures the grasping ability score (GAS) and partial GASs of hand prostheses where the scores represent a percentage of healthy limb function overall and in the individual grasp types assessed by AHAP respectively. The SATH scored an overall GAS of 75% and scored above 50% for every partial GAS measurement and above 75% for five of the eight grasp types and both non-grasping tasks. These results were comparable to scores obtained by a more advanced prosthesis. Generally, the SATH performed satisfactorily in AHAP and with some minor modifications to address the lower partial GAS scores will be ready for clinical validation in an upper-limb amputee population.

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List of Abbreviations

ADL	Activities of Daily Living
AHAP	The Anthropomorphic Hand Assessment Protocol
BCI	Brain-Computer Interface
CAD	Computer-Aided Design
CG	Cylindrical Grip
DIP	Distal Interphalangeal Joints
DOF	Degrees of Freedom
DVG	Diagonal Volar Grip
EEG	Electroencephalography
EG	Extension Grip
EMG	Electromyography
GAS	Grasp Ability Score
GT	Grasp Type
H	Hook
INR	Indian Rupees
IOF	Index of Function
IP	Index Point
KIT2	The Kit Prosthetic Hand P2
LMICs	Lower to Middle-Income Countries
LP	Lateral Pinch
MCP	Metacarpophalangeal Joints
Opp.	Opposition
P	Platform
PIP	Proximal Interphalangeal
PP	Pulp Pinch
PWM	Pulse Width Modulation
SATH	Self-Actuated Tenim Hand
SG	Spherical Grip
SHAP	The Southampton Hand Assessment Procedure
SUS	System Usability Scale
TP	Tripod Pinch
ULPOM	Upper Limb Prosthetic Outcome Measures
VC	Voluntary Closing
VF	Virtual Fingers
VO	Voluntary Opening
YCB	Yale-CMU-Berkeley

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1 Introduction

1.1 Background to Study

An estimated 22.3 million people live with unilateral (11 million) or bilateral (11.3 million) upper-limb amputations(McDonald, Westcott-McCoy, Weaver, Haagsma, & Kartin, 2020). In lower to middle-income countries (LMICs), upper-limb amputees are generally limited to utilising body-driven or passive prosthetics. While there is much research in advanced myoelectric prosthetics, these prostheses are generally unaffordable for those in less developed countries and can also be unattainable for those in more developed nations. Myoelectric prostheses can cost between R300,000 and R1,000,000 while body-driven prostheses may cost between R10,000 and R15,000. Body-driven prostheses including hand and hook variations do offer some useful functionalities for acts of daily living (ADLs), however, they often require excessive effort forces to activate. Alternatively, passive prosthetics are primarily used for aesthetic appeal but have limited functionality.

Users of body-driven prostheses often abandon them due to the overexertion of their shoulder in operating these devices leading to eventual overuse syndrome of the healthy limb (Jayakumar, Thirunavukkarasu, Kalpana, & Ramesh, 2017). The combination of the high cost of myoelectric prostheses and the relatively low grasping capabilities of body-driven prostheses has led to there not being a suitable prosthetic solution for those in developing countries or those from poorer backgrounds. Thus, amputees in LMICs need a cost-effective prosthetic solution that will provide more functionality than that of traditional body-driven prostheses while also reducing the amount of physical effort required to operate the prosthesis.

1.2 Aim

This study aims to design an electromechanical hand prosthesis that meets the functional and grasping requirements of prosthesis users, thereby bridging the functional gaps between body-driven and myoelectric prostheses.

1.3 Objectives

To achieve the aim of this project certain objectives need to be met. These objectives can be grouped into three main categories, namely: Problem Identification; Prosthesis Design; and Design Validation. The primary objectives and their associated sub-objectives are outlined below:

- Identifying the upper limb functional requirements through a thorough review of the literature and clinician consultation:
    - Identifying the essential grasping capabilities of a functional prosthesis.
    - Identifying reasons for prosthesis abandonment.
    - Identifying other concerns important to prosthesis users.
- The design refinement of an existing prosthesis, the Tenim Hand, and the subsequent development of a functional prosthesis through:
    - Refining the design of the Tenim Hand to meet the functional shortfalls of the original design.
    - The design of a prosthesis that addresses the concerns and requirements discovered from the literature and can perform the identified essential grasps.
    - The design of an actuator system that is integrated into the mechanical design of the prosthesis.
- Performing design validation of the prosthetic with its integrated actuator system through the independently developed protocol for assessing hand function: The Anthropomorphic Hand Assessment Procedure (AHAP)

1.4 Scope and Limitations

The project was completed as the fulfilment of the minor dissertation portion of the author's master's degree (6 to 9 months or 90 credits). The scope of this study was thus limited to the design and development of a proof of concept hand prosthesis and the subsequent design validation. The design validation was completed without the utilisation of patient participants and was primarily focused on assessing whether the device was ready for pre-clinical testing and identifying the improvements that should be made before then. Further research and development that would ideally accompany the work conducted in this dissertation are included in the recommendations for future work in Chapter 7.

1.5 Dissertation Overview

This dissertation documents the research and design processes and outcomes completed in the study. The chapters presented in this dissertation broadly follow the sequence in which the different research tasks were conducted and are highlighted in Figure 1.1. The dissertation begins with the Introduction presented above followed by a review of the literature focused on the human hand, amputees and prostheses in Chapter 2. The knowledge gathered in the literature review was used to develop and select the design considerations highlighted in Chapter 3 which in turn were used to develop the prosthesis described by the design outcomes presented in Chapter 4. The experimental methodology followed in the design validation process is presented in Chapter 5 after which the subsequent results are presented and discussed in Chapter 6. Finally, conclusions are drawn and recommendations for future work are given in Chapter 7.

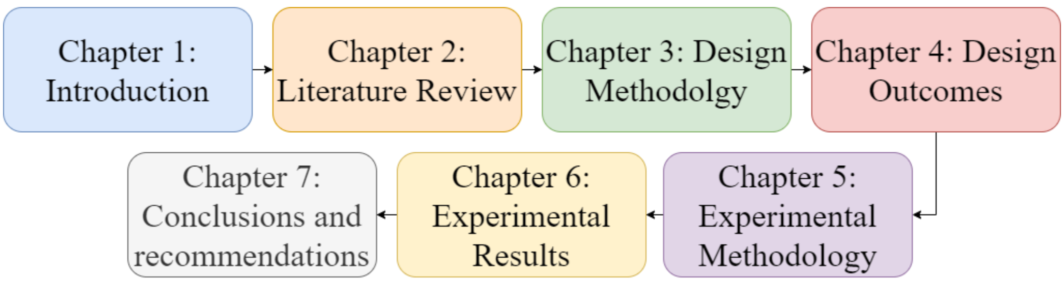


Figure 1.1 Flow chart illustrating an overview of the dissertation outline

2 Literature Review

This chapter seeks to review the relevant literature around the human hand and upper limb amputees and prosthetics. The chapter begins with a description of the Tenim Hand, a low-cost functional body-powered prosthesis. The anatomy of the hand and wrist are then described followed by a summarisation and ranking of the different grasp types. The needs of upper limb amputees are then explored, and existing prostheses are discussed. Finally, potential methods of evaluating prostheses are explored and discussed.

2.1 The Tenim Hand

The Tenim Hand project was started with the aim of developing an affordable, anthropomorphic prosthetic hand that was both highly functional and aesthetically appealing (Tenim, 2014). The Tenim Hand, shown in Figure 2.1, is a body-driven hand prosthesis that is controlled using cables attached to a shoulder harness. It was designed as a low-cost prosthesis that is accessible to low and middle-income patients while overcoming the excessive forces required to actuate traditional body-driven prostheses. The device was to be functional enough to assist patients in performing their ADLs while also being aesthetically pleasing in appearance.

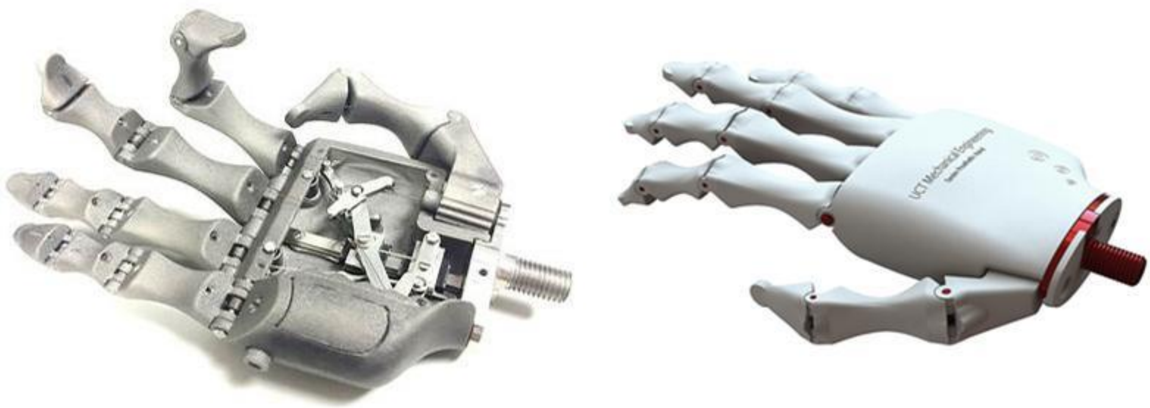


Figure 2.1 A photograph showing the internal mechanisms of the Tenim Hand and a rendered image showing the dorsal surface of the hand.

The Tenim Hand is anthropomorphic and can perform multiple different grasp types. Using a single cable attached to the shoulder harness, the hand is controlled through activation of the amputee's shoulder. The prosthesis uses tendon-based finger mechanisms which are connected to the single input cable through underactuated differential levers. Underactuation allows the prosthesis to actuate multiple outputs through activation of the single input cable. Once the hand has been activated and the fingers have been moved from the neutral open position the user can choose to engage a ratchet and pawl mechanism that locks the grasp, otherwise, torsion springs in the finger joints extend the fingers back to the neutral position.

The tendon-based finger system, illustrated in Figure 2.2, comprises three 3D-printed phalangeal parts that contain channels for the threading of the tendons. Channel tubing run through the length of each phalangeal channel and is capped by channel rings. The phalangeal parts are hinged by joint pins around which torsion springs sit. Torsion springs perform the extension functions of the hand. The components of the finger system are illustrated in Figure 2.3. The four fingers are attached to the palmar body via additional joint pins.

The thumb contains two phalanges and a thumb swivel mechanism analogous to the first metacarpal of the human hand. A swivel mechanism, shown in Figure 2.4, comprises the thumb swivel and the incremental locking mechanisms. Manual abduction or adduction is achieved by adjusting the thumb swivel mechanism. A bearing inside the thumb redirects the tendon cable of the thumb to its terminus at the thumb transfer lever.

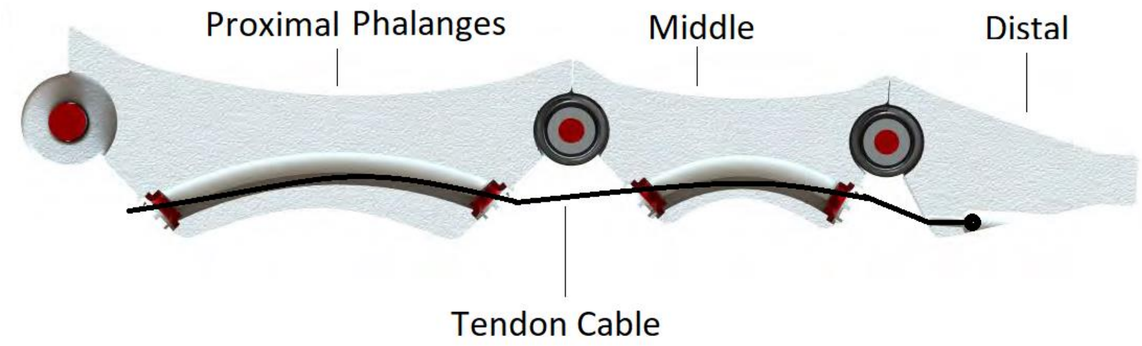


Figure 2.2 Tension-cable based tendon system of the Tenim hand (Tenim, 2014)

The palmar body houses the many components that allow the actuation of the Tenim Hand. These include the differential lever mechanism, the thumb transfer lever and the pulley-ratchet slider. The palmar body and the various systems it contains is shown in Figure 2.5.

The thumb transfer lever translates the force from the palmar actuating cable to the tendon cable of the thumb. A Palmar actuating cable runs from the thumb transfer lever around two sets of bearings located at the distal end of the palmar body and then down through the pulleys of the ratchet-pully slider to its terminus at the clamp on the differential lever carriage.

The differential lever system provides a means for underactuation and allows the fingers to conform around an object irrespective of its shape. There are two secondary levers and a single primary lever. The primary lever sits on a carriage that slides on a linear bearing. Each secondary lever is attached at its fulcrums to the two ends of the primary lever. The secondary levers are then connected at their respective lever-ends to one of the tendon cables of the fingers.

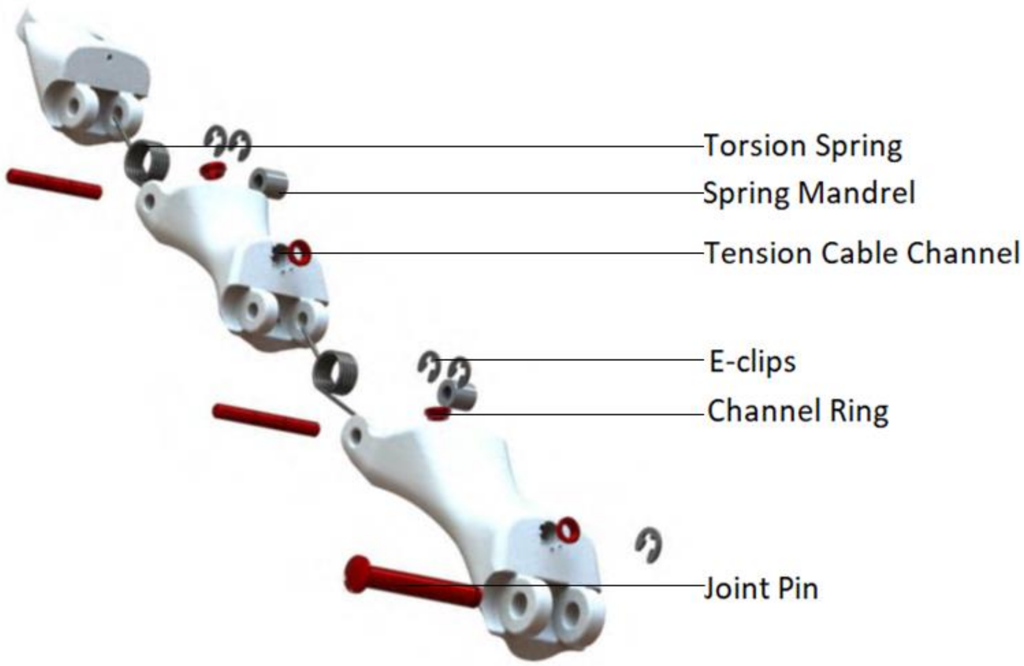


Figure 2.3 Components of the fingers of the Tenim hand (Tenim, 2014)

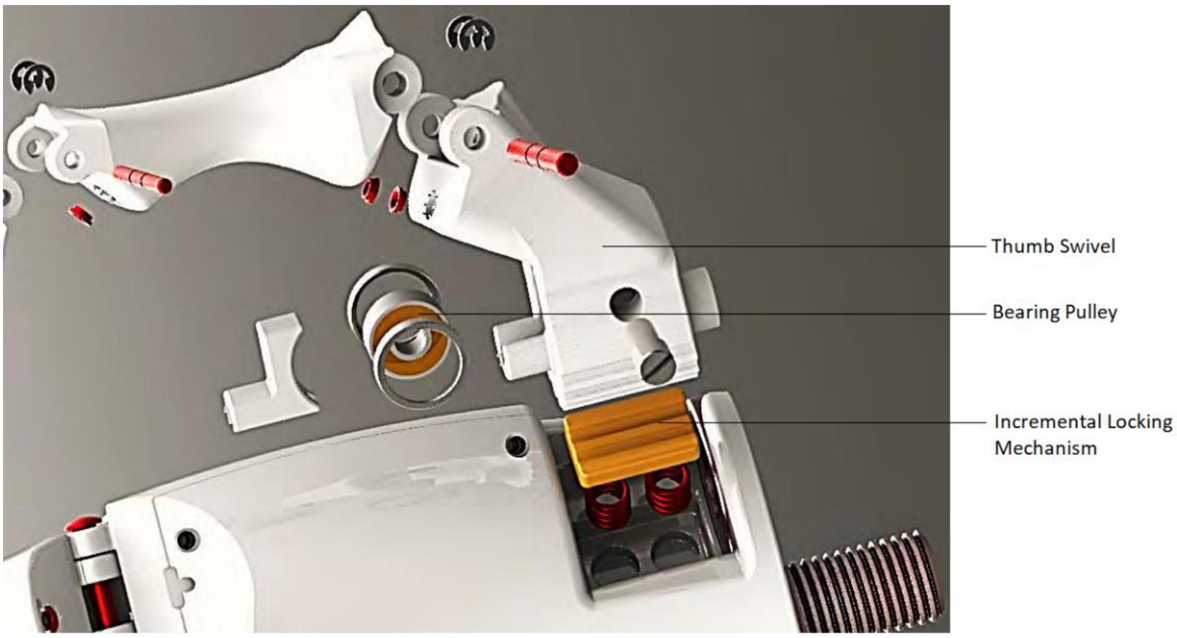


Figure 2.4 The thumb of the Tenim Hand showing the thumb swivel and incremental locking mechanism (Tenim, 2014)

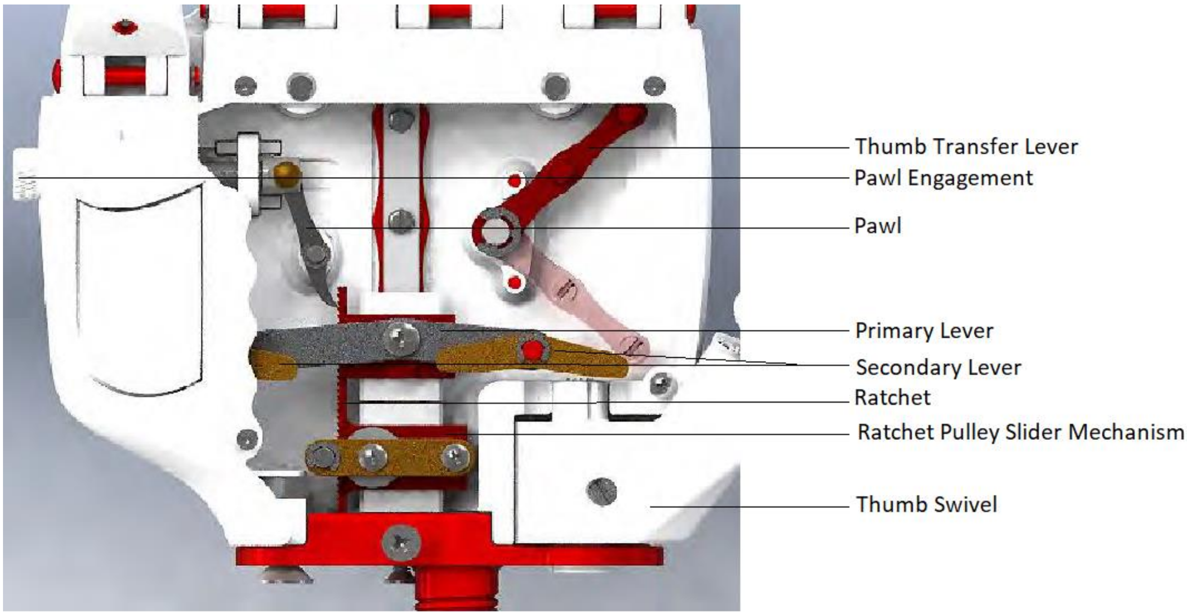


Figure 2.5 Palmar body and its housed components (Tenim, 2014)

Positioned on the same linear bearing is the ratchet-pulley slider mechanism that redirects the palmar actuating cable to the thumb transfer lever from the differential lever slider carriage. The ratchet pulley slider, when combined with the pawl engagement mechanism, allows for incremental locking of the hand in flexion. The primary actuating cable terminates at the distal end of the slider and exits the palmar body proximally through the wrist stem. The cable routing can be seen in Figure 2.6.

The mechanical design of the Tenim Hand with its differential lever system and its adjustable thumb ensued in the Tenim Hand being particularly versatile in its grasping capabilities. It was physically capable of performing most grasp types used in activities of daily living (ADL) and provided increased efficiency of input to output force transfer when compared to other body-driven prostheses. A functional review of the Tenim Hand's capabilities can be found in 7.2.2Appendix A.

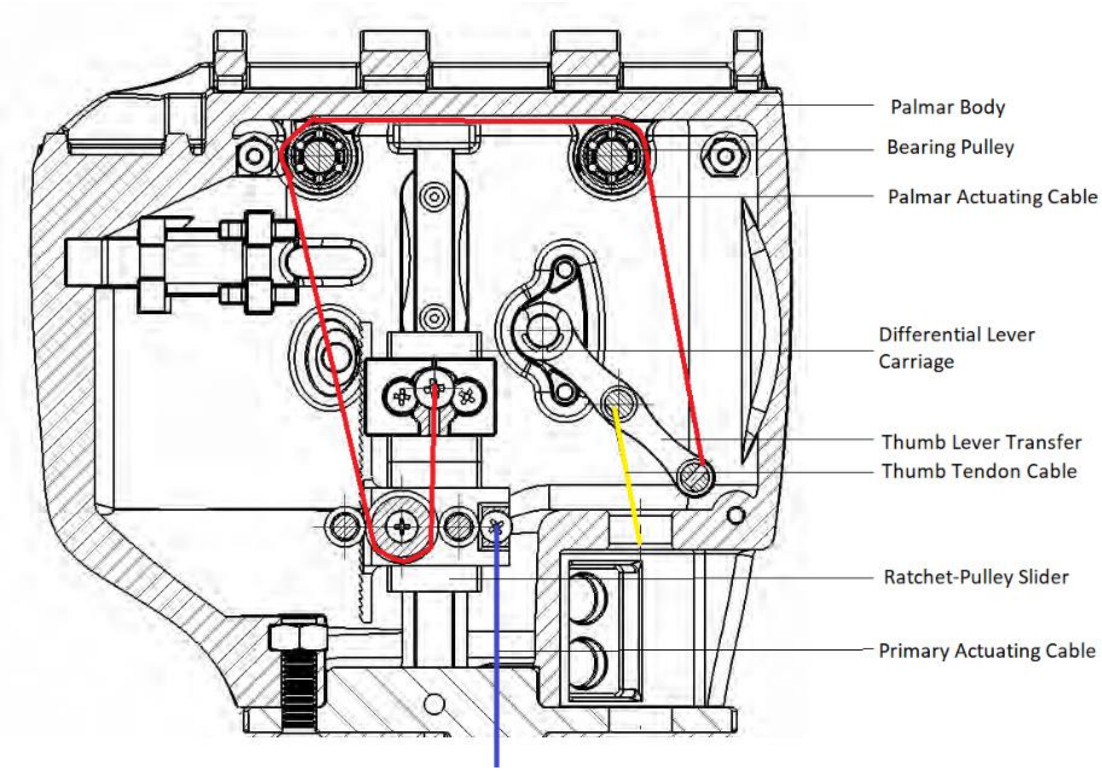


Figure 2.6 Cable routing for the Tenim Hand (Tenim, 2014)

The Tenim Hand was an attempt at addressing the need for a cost-effective prosthetic solution that would provide more functionality than that of traditional body-driven prostheses. However, while versatile in its grasping capabilities, the hand was not always able to perform the required grasp without intervention from the healthy limb of the user. This would lead to the healthy limb being encumbered while grasping an object. Additionally, the Tenim Hand, despite being force transfer efficient, still required excessive exertion of the user's shoulder. Intuitively these factors would greatly reduce the usability of the device. Nevertheless, the notable features of the Tenim Hand lends the hand to be a promising starting point for the development of a prosthesis suitable for those living in LMICs.

2.2 Anatomy of the Hand and Wrist

The human hand is a complex network of muscles, nerves and bones that combine to provide humans with what is arguably the finest dexterity in the animal kingdom. To attempt to replicate its functionality one must understand the underlying anatomy of the hand.

2.2.1 Bones and joints of the hand

The structure of the hand is primarily provided by the 27 bones contained within (Gilory, Macphearson, & Ross, 2012). These bones vary significantly in size and shape and can be categorized into three groups; namely the phalanges, the metacarpals and the carpals. The phalangeal bones form the fingers and the thumb. The 2^{nd} to 5^{th} digits are comprised of 3 phalangeal bones each, i.e. the proximal, middle and distal phalanges, whereas the thumb only has the proximal and distal phalanges. The palm is made of 5 metacarpals which articulate to a proximal phalanx on each of their distal ends. The proximal ends of the metacarpals articulate with the carpal bones which in turn form the wrist. In the Tenim Hand, each phalanx of an anatomical hand is represented by a phalangeal part whereas the metacarpals, excluding the 1^{st} metacarpal, and the wrist bones are formed by a single palmar part. The 1^{st} metacarpal is represented by a thumb swivel component that allows manual opposition of the thumb. Figure 2.7 shows the bones of the hand alongside the comparable structural components of the Tenim Hand.

The joints in the hand connect the bones in the hand to each other while allowing for defined movements. The joints of the hand that have been reproduced in the Tenim Hand are the interphalangeal joints (phalanx to phalanx joints) and the metacarpophalangeal joints (phalanx to metacarpal/palmar body joints). Figure 2.8 shows the joints of the hand that are replicated in the Tenim Hand alongside the equivalent joints of the Tenim Hand.

2.2.2 Muscles of the Hand

The muscles in the hand work in harmony to aid humans in completing their ADLs. Most muscles in the hand perform one or two actions that when performed in conjunction with other muscles combine to produce complex movements. These actions include flexion, extension, abduction, adduction and opposition. Figure 2.9 shows the flexor (palmar) and extensor (dorsal) compartments of the hand and the muscles they contain.

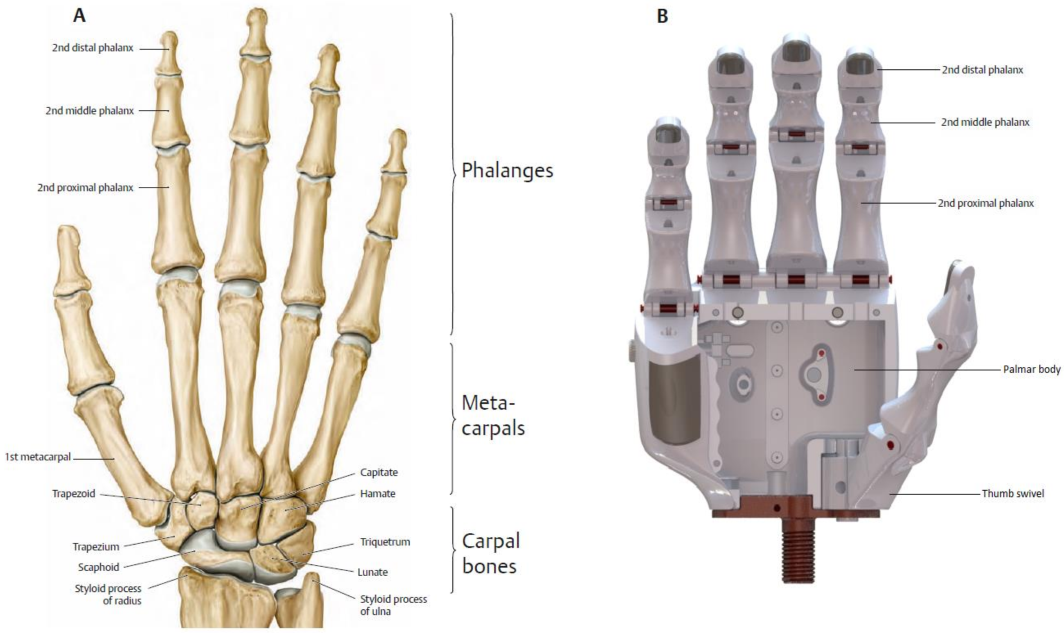


Figure 2.7 Palmar view of articulated bones of the hand (A), adapted from Gilroy et al. (2012), and palmar view of the structural components of the Tenim Hand (B)

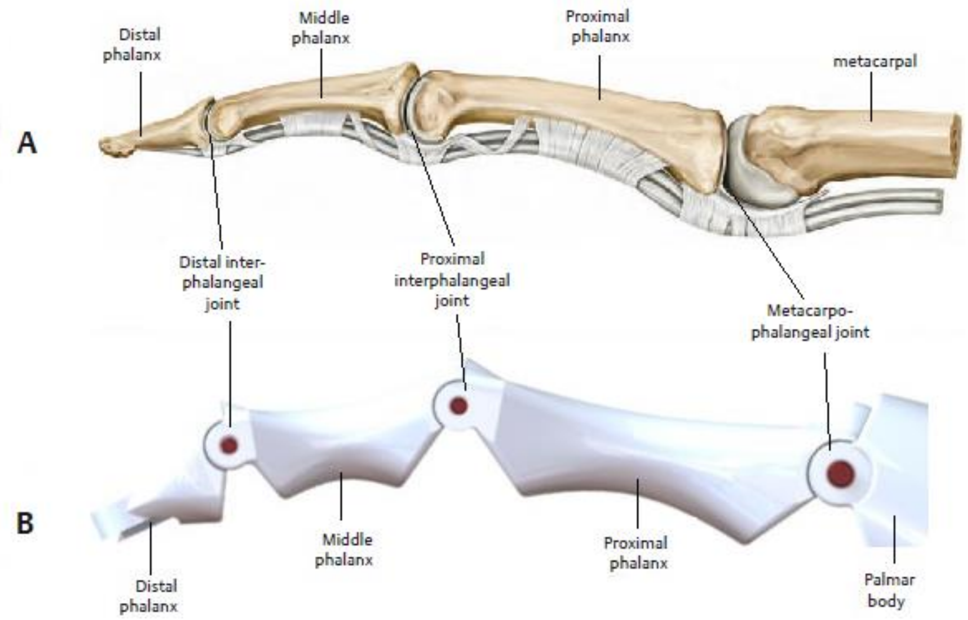


Figure 2.8 The interphalangeal and metacarpophalangeal joints of the hand (A), adapted from Gilroy et al. (2012) and a rendered image of the equivalent joints in the Tenim Hand (B)

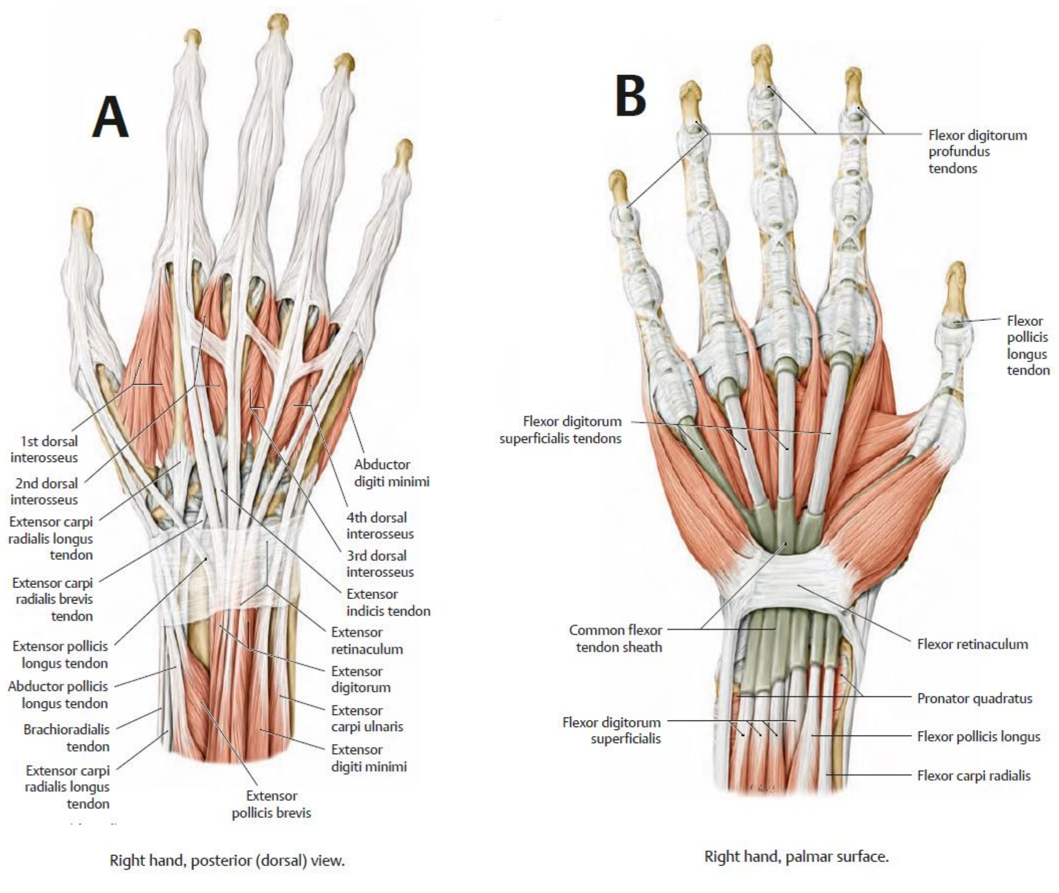


Figure 2.9 Dorsal (A) and palmar view of the muscles of the hand, adapted from Gilroy et al. (2012)

To reproduce some of the functional versatility of an anatomical hand, the Tenim Hand had to replicate some of the actions that the muscles in the anatomical hand produce. The Tenim Hand uses a cable-based tendon system driven through a single input to cause flexion in the joints of the fingers. The actions this mechanism replicates are those of the flexor muscles of the hand. Replicating the effect of the extensor muscles, i.e. extension, was achieved using spring-loaded interphalangeal and metacarpo-phalangeal joints. The opposition of the thumb in the Tenim hand is a manual process that requires the user to use their free hand or simply bump the thumb on a hard surface to manually oppose the thumb swivel mechanism. Actions such as supination and pronation of the hand, abduction and adduction of the wrist and wrist flexion and extension were not replicated. Table 2-1 compares some of the anatomic muscles of the hand and their functions with the mode through which the Tenim Hand replicates these actions.

2.3 Grasping

2.3.1 Grasp Types

The different prehensile grasp types of the hand can be classified by the need for precision or power; the opposition of the grip; the number of virtual fingers required and the position of the thumb in the grip. These four classification criteria are discussed below.

Power, Intermediate and Precision Grasps

Grasps of the hand can be classified by their requirement of precision or power. Napier (1956) defined precision grips as those in which the object is pinched between the fingers and the thumb, whereas in power grips the object is clamped between the fingers and the palm with the thumb aiding in opposing the pressure from the fingers. A third category, known as intermediate categories, was later added which involved grips that combined the characteristics of the precision and power grips (Kamakura, Matsuo, Ishii, Mitsuboshi, & Miura, 1980).

Table 2-1 Comparison of the muscles of the human hand and the actions they produce with the Tenim Hand's mode of replicating the action

Muscle	**Primary Action (Gilroy, Macphearson, & Ross, 2008)**	**Mode of function replication in Tenim Hand (Tenim, 2014)**
Flexor Digitorum Profundus	Flexes distal interphalangeal joints (DIP) (2nd to 5th digits)	Actuating cable tendons
Flexor Digitorum Superficialis	Flexes proximal interphalangeal (PIP) joints (2nd to 5th digits)	
Flexor Pollicis Longus	Flexes thumb	
Opponens	The opposition of the thumb	Manually adjustable thumb opposition
Extensor Pollicis Brevis	Extends thumb metacarpophalangeal (MCP) joint	Spring-loaded metacarpophalangeal and interphalangeal (distal and proximal for 2nd to 4th digits) joints
Extensor Pollicis Longus	Extends thumb interphalangeal joint	
Extensor Indicis	Extends index finger (2nd digit)	
Extensor Digitorum	Group finger extension (2nd to 5th digits)	
Extensor Digiti Minimi	Extends little finger (5th digit)	
Extensor Carpi Radialis Brevis	Extends wrist	Currently not replicated
Extensor Carpi Radialis Longus	Extends wrist	
Extensor Carpi Ulnaris	Extends wrist	
Flexor Carpi Radialis	Flexes wrist	
Flexor Carpi Ulnaris	Flexes wrist	
Pronator Teres	Forearm Pronation	
Pronator Quadratus	Forearm Pronation	
Supinator	Forearm supination	
Anconeus	Extends the elbow	
Brachioradialis	Flexes forearm	
Abductor Pollicis Longus	Abducts thumb	
Abductor Pollicis Brevis	Abducts thumb	
Adductor Pollicis	Adducts thumb	

Pad, Palmar and Side Opposition

Opposition when referring to grasps refers to how the forces required to grip an object oppose each other (Thea Iberall, 1997). Pad opposition occurs between the palmar surfaces of fingers and thumb where the forces occur parallel to the palmar surface. Palmar opposition occurs between the fingers against the palmar surface where the forces are perpendicular to the palmar surface. Side opposition occurs generally between the sides of the fingers where the force applied is transverse to the palmar plane.

Virtual Fingers

Virtual fingers (VF) are functional units that describe fingers that apply forces in a similar direction (T. Iberall, 1987). Fingers acting in the same direction are considered to be part of the same virtual finger. Virtual fingers in prehensile grasps oppose each other to grip an object.

Thumb Position

Thumb position simply refers to whether the thumb is adducted or abducted.

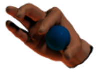
The GRASP Taxonomy

Using the four classification criteria Feix, Romero, Schmiedmayer, Dollar & Kragic (2016) developed a taxonomy that classified 33 different prehensile grasps dubbed “The GRASP Taxonomy”. The GRASP taxonomy was synthesised through reviewing and evaluating 22 previously studied taxonomies in the literature. Table 2-2 shows a visual representation of the GRASP taxonomy.

2.3.2 Ranking of Grasp Types

Ideally, a prosthetic hand would be functionally equivalent to the missing limb, however, cost and engineering constraints necessitate that only the most used grasps be included in the design of the prosthetic hand.

Table 2-2 the 33 prehensile grasps as classified in the GRASP Taxonomy. Grasps are classified by their opposition (Opp) and the number of virtual fingers involved (VF) adapted from Feix et al. (2016).

	Power						Intermediate			Precision				
Opp:	Palm		Pad				Side			Pad				Side
VF:	3-5	2-5	2	2-3	2-4	2-5	2	3	3-4	2	2-3	2-4	2-5	3
Thumb Abducted		1: Large Diameter  2: Small Diameter  3: Medium Wrap  10: Power Disk  11: Power Sphere 	31: Ring 	28: Sphere 3 Finger 	18: Extension Type  26: Sphere 4-Finger 	19: Distal 	23: Adduction Grip 		21: Tripod Variation 	9: Palmar Pinch  24: Tip Pinch  33: Inferior Pincer 	8: Prismatic 2 Finger  14: Tripod 	7: Prismatic 3 Finger  27: Quadpod 	6: Prismatic 4 Finger  12: Precision Disk  13: Precision Sphere 	20: Writing Tripod 
Thumb Adducted	17: Index Finger Extension 	4: Adducted Thumb  5: Light Tool  15: Fixed Hook  30: Palmar 					16: Lateral  29: Stick  32: Ventral 	25: Lateral Tripod 					22: Parallel Extension 	

In developing the Southampton Hand Assessment Procedure (SHAP), a standardised tool assessing pathologic and prosthetic hand function, Light, Chappell & Kyberd (2002) compiled the nine ADLs tested in the assessment in proportion to Sollerman and Ejeskar's (1995) percentage-use of grasp types. Their percentage-use of each grasp type in the SHAP ADLs are presented in Table 2-3 along with the equivalent grasps as classified in the GRASP taxonomy.

Bullock, Zheng, De La Rosa, Guertler & Dollar(2013) recorded the frequency of different grasp types used by two machinists and two housekeepers. The subjects were recorded for 7.45 hours over multiple days using a head-mounted mobile camera while the subjects were at work. From the video data, approximately 4,700 grasping actions were observed by each subject. The housekeepers used just 5 grasps to achieve 80% of the grasps used, whereas the machinists used 10 different grasp types to achieve a similar percentage. This suggests that machinists use more grasp types on average than housekeepers. It was shown that when looking at all four subjects the top 10 grasps accounted for 80% of the total grasp used by the subjects throughout the study. Table 2-4 shows the average frequency of grasp types used by the machinists and housekeepers. The subjects of this study are by no means representative of the upper limb amputee population nevertheless this study provides valuable insight into the grasp needs for the proletarian amputee.

The two studies discussed above were used to develop a ranked list of grasps presented in Table 2-5. Prosthesis design should ideally incorporate as many of the grasps listed in the table with the greatest priority given to the higher-ranked grasps.

Table 2-3 The percentage-use of each grasp type in SHAP ADLs compared with Equivalent GRASP Taxonomy grasps (Light et al., 2002). *The number in brackets indicates the grasps respective numbering in the GRASP taxonomy.*

SHAP grasp type	**Equivalent grasp types in GRASP Taxonomy**	**Frequency [%]**
Power Grip	Medium Wrap (3)	25
Lateral Grip	Lateral (16)	20
Tip Grip	Tip Pinch (24), Prismatic 2-4 finger (8-6)	20
Tripod Grip	Tripod Grip (14), Writing (20) & Lateral Tripods (25)	10
Spherical Grip	Power Sphere (11), Power Disk (10)	10
Extension Grip	Index Finger Extension (17)	10

Table 2-4 Average frequency grasp types for machinists and housekeepers (Bullock et al., 2013). *The number in brackets indicates the grasps respective numbering in the GRASP taxonomy.*

GRASP Taxonomy grasp type	**Frequency [%]**
Medium Wrap (3)	23.0
Precision Disk (12)	17.0
Lateral Pinch (16)	7.0
Tripod (14)	6.4
Index Finger Extension (17)	5.6
Lateral Tripod (25)	5.3
Power Sphere (11)	4.6
Prismatic 2 Finger (8)	4.5
Light Tool (5)	3.7
Prismatic 3 Finger (7)	3.7

Table 2-5 Ranked list of grasp types for prosthesis design named according to GRASP Taxonomy conventions. The number in brackets indicates the grasps respective numbering in the GRASP taxonomy.

Ranked list of Grasp Types

1. Medium Wrap (3)	8. Power Sphere (11)
2. Precision disk (12)	9. Power Disk (10)
3. Lateral pinch (16)	10. Prismatic 2 Finger (8)
4. Tripod (14)	11. Prismatic 3 Finger (7)
5. Lateral Tripod (25)	12. Light Tool (5)
6. Writing Tripod (20)	13. Tip Pinch (24)
7. Index Finger Extension (17)	

2.4 Upper Limb Amputees

Designing prostheses for real-world use requires an understanding of the needs of the patient. This section aims to discuss upper limb amputees and their needs.

2.4.1 Amputees

Ziegler-Graham, MacKenzie, Ephraim, Travison, & Brookmeyer (2008) reported that in 2005 1.6 million amputees were living in the United States. Of the 1.6 million 35% were upper limb amputees (500,000) of which 8% (41,000) were major amputations. Trauma accounted for 83% (34,000) of all major upper-limb amputations, whereas dysvascular diseases and cancer accounted for the rest. The total number of amputees in the US is expected to increase to 3.6 million by 2050.

Congenital conditions were not included in the study which authors claim accounts for less than one per cent of the total incidence of limb loss and thus their estimate may be conservative. However, when major upper-limb amputations account for only 2.6% of all amputations (41,000 of 1.6million amputees) congenital limb deficiencies, which may only account for less than 1% of total amputations, must still be taken into consideration. Congenital limb anomalies have an incidence of 26 per 100,000 live births of which 58.5% involve the upper limb (Nelson & Kelly, 2010). If this rate is extrapolated over a global population of 7.3 billion, then it suggests that roughly 1,000,000 people live with upper limb congenital deficiencies. The ratio between the total incidence of limb loss and congenital limb deficiencies presented in Ziegler-Graham et. al.'s study implies more live with trauma-related amputations.

LeBlanc estimated that in 2008 2.4 million people with upper limb amputations live in LMICs (2008). This suggests that the relatively expensive myoelectric prostheses are not suitable for most upper-limb amputees. When looking at more developed countries such as the United States the incidence of amputations is greater in populations suffering from poverty (Feinglass et al., 2000). The higher incidence may be related to manual labour occupations having greater probabilities of work-related injuries and those workers having lower access to healthcare.

2.4.2 Amputee Needs

In a study examining the needs of upper limb prosthetic users in India, Nagaraja Bergmann, Sen & Thompson(2016) interviewed 60 lower and middle-income patients with cosmetic (26), body-powered (30) and myoelectric (4) prostheses. When patients were asked to rank reasons for non-wear comfort, function and maintenance were the biggest complaints. Furthermore, the patients ranked functionality, comfort and durability as their greatest design priorities. Interestingly, when ranking the satisfaction of the patients on different aspects of their prostheses, including colour, shape, noise, appearance, weight, usefulness, reliability, fit, comfort and overall satisfaction, patients were generally neutral or satisfied except for with comfort and weight. In these two aspects, the patients were generally dissatisfied. Only myoelectric prosthesis users responded neutrally to their satisfaction of comfort. Although, cosmetic and body-driven prostheses were available at less than 7,000 Indian Rupees (INR) the patients were willing to pay up to INR 20,000, in instalments, if the devices offered enhanced functionality and durability.

Another Indian study reporting on 40 patients, reported that 65% of the patients were fully independent, 25% were partially dependent and 10% were fully dependent on others(Jayakumar et al., 2017). It is no coincidence that all four bilateral amputees that partook in this study made up the group of fully dependent patients. All 40 patients had received either cosmetic or body-driven prostheses (a total of 44 due to their being four bilateral amputees) from the Government Institute of Rehabilitation Medicine, Chennai, India. 24 of the prostheses were body-powered, 20 were cosmetic and an additional four myoelectric were acquired prostheses through private means. 22 out of 24 body-powered prosthesis users had abandoned their prosthesis after only a month citing inadequate function and shoulder pain while none of the cosmetic or myoelectric prosthesis discarded theirs. The myoelectric prosthesis users along with four cosmetic prosthesis users reported using their prosthetic for longer than 8 hours per day while the remaining four patients (two cosmetic and two body-driven) used their prostheses for less than four hours per day. The high usage of myoelectric prostheses suggests that there is a desire for active prostheses but the negative aspects of body-driven prostheses are not worth enduring. 35 % of the patients reported overuse injuries in the sound limb. Overuse is particularly notable due to the high rate of independence combined with high rejection rates. This implies that many patients are exclusively using their sound limbs to perform acts of daily living.

In a smaller-scale study on seven American patients, similar issues were raised (Benz et al., 2016). In this study, the interviewers were conducted in an open-ended manner to avoid imparting biases on the patients. Common themes were once again centred around discomfort. The patients reported discomfort on both their amputated side and their able side. Discomfort on the amputated side attributed to poor socket fit and fatigue, caused by weight and required effort, in the arm, shoulders and back. Discomfort on the sound side was attributed to overuse syndrome caused by overworking the healthy limb and other compensatory movements. Symptoms of overuse syndrome include; tendinitis, arthritis and carpal syndrome. Additional themes raised were the difficulties with precise hand or finger movements and the difficulties of using prostheses in the workplace for activities such as typing and using a mobile phone. Interestingly, six of the seven patients reported having multiple prostheses. Six patients had myoelectric prostheses, one had a cosmetic prosthesis, two had body-driven hooks while four had specialised sports prostheses. This suggests that while costs are not as big a factor in treating their disability when compared with those in the Indian study, nevertheless, due to owning multiple prostheses costs may be a factor in selecting individual prostheses.

Bajaj, Spiers and Dollar in a review of the state of the art of prosthetic wrists investigated the use of wrists in both research prostheses and those that are commercially available (2019). It was found that single degree of freedom (DOF) wrists, supination and pronation, contributed significant functionality to a prosthetic system and are desired by prosthesis users (Atkins, Heard, & Donovan, 1996). Additionally, higher DOF wrists that may include wrist flexion or radial deviation were also desired and shown to improve function but when implemented they tended to add significant length to a prosthesis. This is due to the mechanisms being used to add DOFs being stacked in series to each other. It is possible to have a single mechanism providing multiple DOF to the prosthesis however this may significantly increase costs and complexity for low-cost devices.

In summary, the following priorities are identified from the literature as priorities for effective prosthesis design:

- The comfort of the prosthesis
- Enhanced functionality (when compared to body-driven prostheses)
- The durability of the prosthesis
- Limiting overuse of the sound limb
- Cost of the prostheses
- Ability to uses prosthesis in the workplace
- Wrist pronation and supination

2.5 Existing types of Prosthetic Hands

2.5.1 Passive prostheses

Prostheses that require an external force to adjust their grasping mechanism, if the mechanism is adjustable at all, are known as passive prostheses. In an attempt to avoid confusion between the different passive prostheses, Maat, Smit, Plettenburg and Breedveld (2018) created a classification system for the passive prosthesis. In their system, passive prostheses can be divided into anthropomorphic prosthetic hands and instrument-like prosthetic tools. Each group is then further subdivided into static and adjustable groups. Where the static group are fixed and cannot be adjusted, whereas adjustable prostheses can have the prostheses adapted by an external force to grasp or manipulate objects. Maat et al.'s classification is shown in Figure 2.10.

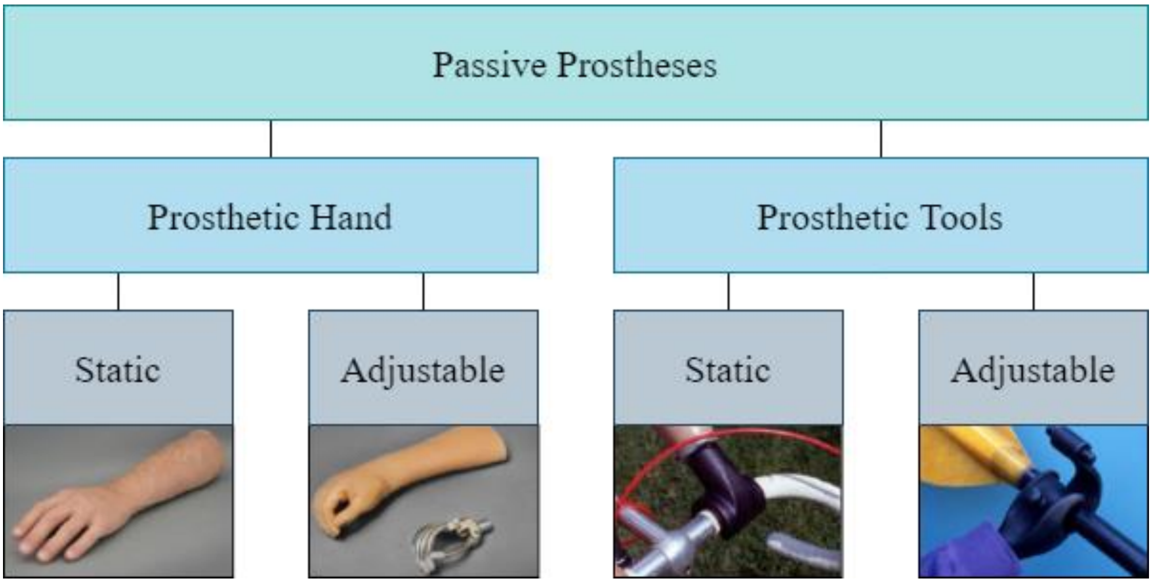


Figure 2.10 Maat et al.'s passive prosthetic classification system adapted from Maat et al. (2018)

Despite their similarities passive prosthetic tools and passive prosthetic hands are used slightly differently. Passive prosthetic hands are used for social purposes and can aid in non-manipulative activities (Fraser, 1998; Pillet & Didierjean-Pillet, 2001). Passive prosthetic tools, however, can be used for activities including recreation, driving and ADLs such as cycling and eating and are often purpose-built (Maat et al., 2018).

2.5.2 Active Prostheses

Active prostheses are those that use a force applied internally to the prosthesis to control the prosthesis(Maat et al., 2018). Active prostheses primarily consist of body-driven and myoelectric prostheses. These two groups of active prostheses are described below. Research on other types of active prostheses such as electroencephalography (EEG) based brain-computer interface (BCI) controlled prostheses continues to be completed, yet there does not seem to be any prosthetic devices available on the market (Micera et al., 2010; Warren et al., 2016).

Body-driven prostheses employ shoulder harnesses that capture the relative motion of the shoulder to the arm to activate the prosthesis (Hichert, Abbink, Kyberd, & Plettenburg, 2017). The prosthesis can be in the form of a prosthetic hand or a prosthetic tool, such as a hook, which may be voluntary-closing (VC) or voluntary-opening (VO).

Where VC body-driven prosthesis require user effort to close the prosthesis and VO prosthesis require effort to open the device. Figure 2.11 shows an amputee with a shoulder harness and body-driven prosthetic hook.

Myoelectric prostheses are self-actuated devices that measure electromyographic (EMG) signals in the muscles of an amputee to control an electromechanically or pneumatically actuated hand or prosthetic tool. The myoelectric signals are interpreted by an integrated microprocessor through which an appropriate control action is calculated. The actuator is then activated per the control action to achieve the desired hand movement. Figure 2.12 shows the components of a typical myoelectric prosthesis.

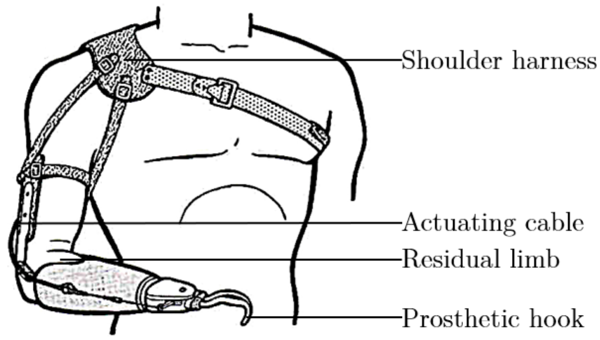


Figure 2.11 Patient with a body-driven prosthesis and shoulder harness adapted from Pursley (1955)

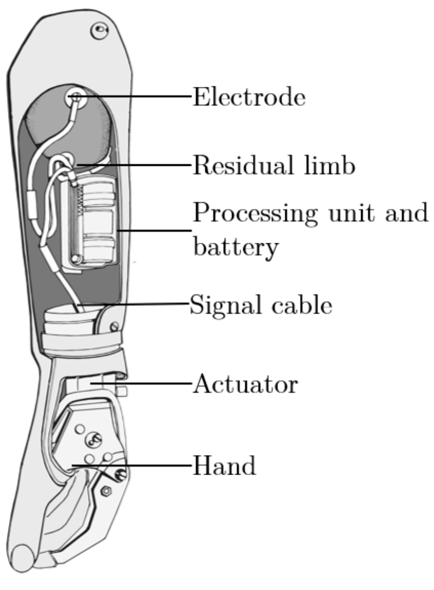


Figure 2.12 Typical components of a myoelectric prosthesis adapted from Radcliffe (2020)

2.5.3 Comparison of Myoelectric and Body-Driven Prostheses

Carey, Lura & Highsmith (2017) conducted a literature review on the differences in myoelectric and body-driven prostheses. Their report found that body-driven prostheses are more durable and require less maintenance while requiring less training time and being cheaper than myoelectric prostheses. They can also be adjusted for comfort more easily and can provide better sensory feedback for the users. Improving cable systems and optimizing the shoulder harness may also improve control of these prostheses. In contrast, myoelectric prostheses are aesthetically superior. They are better for light-intensity work, they can reproduce more grasp types and they reduce phantom pain. The literature lacks the evidence to conclude that one type is superior to the other thus, the review concluded that selection of which type of prostheses should be used should be assessed on a per-patient basis that should be based on the advantages of each prosthesis.

2.6 Methods of Evaluation

Validation of a prototype of any kind requires some measure of function. This section aims to identify validation tools that may be used in the design validation phase of this project.

2.6.1 Usability

A system usability scale (SUS) is a tool for measuring usability consisting of 10 Likert scale questions (Brooke, 1996). SUS can be used for almost any system in which usability has importance. Studies have shown that SUS is a highly robust tool that fills the need to easily collect a user's subjective rating providing valuable feedback to designers and those measuring usability(Bangor, Kortum, & Miller, 2008).

2.6.2 Hand Function

The Upper Limb Prosthetic Outcome Measures (ULPOM) Group is a working group that aimed to create a standardised toolkit for assessing function in upper limb prostheses (Hill et al., 2009). The group identifies the Southampton Hand Assessment Procedure (SHAP) as a potential tool for measuring hand function. Shap was initially designed as a tool for measuring pathologic hand function with potential for use in measuring prosthetic hand function (Light et al., 2002). The Anthropomorphic Hand Assessment Protocol (AHAP) is a more recently developed protocol that was specifically designed to measure prosthetic hand function (Llop-Harillo, Pérez-González, Starke, & Asfour, 2019). These two methods for assessing hand function are discussed below.

SHAP

SHAP is a hand function assessment tool that quantitatively measures the functional range of pathologic or prosthetic hands (Light et al., 2002). SHAP has been shown to identify functional capabilities in prosthetic hands (Kyberd et al., 2009). The assessment consists of 12 abstract object tasks and 14 ADLs that involve six different grasp types (see Table 2-4). The objects used in SHAP are standardised and thus ensures repeatability between different research groups using the protocol. Each task is self-timed using a nearby timer by the subject. The data is recorded in a SHAP computer program that calculates the index of function (IOF); a percentage measure of hand function. Calculating the IOF incorporates a mathematical comparison of the times recorded to complete the tasks and ADLs with a normative data set for healthy hand function. A score of 100% or better would indicate hand function equal or better than that of the human hand, conversely, a score of 0% would indicate that the prosthesis adds no measurable amount of hand function to the amputee. The assessment takes approximately 20 minutes after which the researchers can quantify and compare the performance of unilateral prostheses.

AHAP

AHAP like SHAP is a quantitative hand assessment tool that measures hand function with a specific focus on prostheses (Llop-Harillo et al., 2019). AHAP includes the completion of 26 tasks grasping 25 different objects from Yale-CMU-Berkeley (YCB) Object and Model Set. The YCB Object and Model Set is a standardised set of objects and CAD models intended for use in benchmarking robotic grasping and manipulation studies (Calli et al., 2015). Using this standardised object set allows for reproducibility between different research groups. The tasks are divided into eight grasp types and two non-grasping tasks. The tasks are repeated three times each and are scored against predetermined criteria. The output measurement of AHAP is the grasping ability score (GAS), which like the IOF in SHAP gives a percentage measurement of healthy hand function. Partial GAS scores which measure the GAS for a specific grasp type also allow researchers and designers to identify and assess weaknesses in specific grasp types.

3 Design Methodology

This chapter outlines the design of a prosthesis that bridges the functional gaps between body-driven and myoelectric prostheses. From Chapter 1.3, the design objectives were stated as:

> *The design refinement of an existing prosthesis, the Tenim Hand, and the subsequent development of a functional prosthesis through:*
>
> - *Refining the design of the Tenim Hand to meet the functional shortfalls of the original design.*
> - *The design of a prosthesis that addresses the concerns and requirements discovered from the literature and can perform the identified essential grasps.*
> - *The design of an actuator system that is integrated into the mechanical design of the prosthesis.*

The Tenim Hand was chosen as a basis on which a prosthesis that could achieve this objective would be developed. The Tenim Hand was selected for its improvements in input to output force transfer efficiency and its already versatile grasping capabilities. While there were issues with the original Tenim Hand, these issues were to be addressed as part of the design and prototyping processes.

3.1 Systems Overview and Design Process

Conceptually, a self-actuated prosthesis was selected as the most viable approach to meeting the design requirements because of the inherent high input forces required from body-driven prostheses. A self-actuated prosthesis can be separated into two primary subsystems, namely: the hand and wrist; and the actuation system. The hand and wrist system is comprised of the prosthetic hand, in this case, a modified Tenim Hand and wrist, and are both mechanical in essence. The actuation system is comprised of various electronic and electromechanical components including the actuator, trigger mechanism, controller and power supply. Figure 3.1 shows a systems overview of the proposed prosthesis.

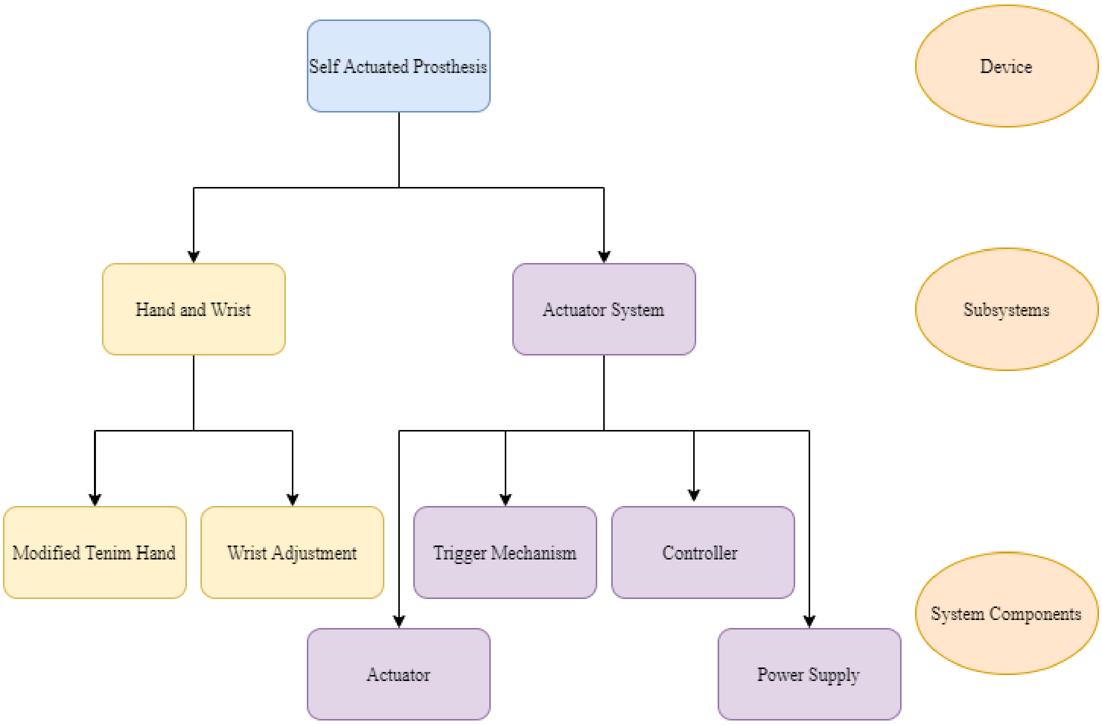


Figure 3.1 Systems overview of the self-actuated prosthesis

The design process that was followed is highlighted in Figure 3.2. The process commenced with the preliminary steps of completing the background research included in the Literature Review and the replication of the original Tenim Hand. Replication of the Tenim Hand allowed the researcher to gain a working understanding of the Tenim Hand and its features and limitations. The replication of the Tenim Hand was accomplished using the CAD files, technical documents and existing parts made available by Assoc. Prof. George Vicatos. The remainder of the design process was then split into three integrative sections grouping similar work processes together namely: Section I: Hand and Wrist Design; Section II: Actuator System design; and Section III: Systems integration. Each section was completed in sequence starting with Section I and ending on Section III. These sections are discussed in detail later in this chapter.

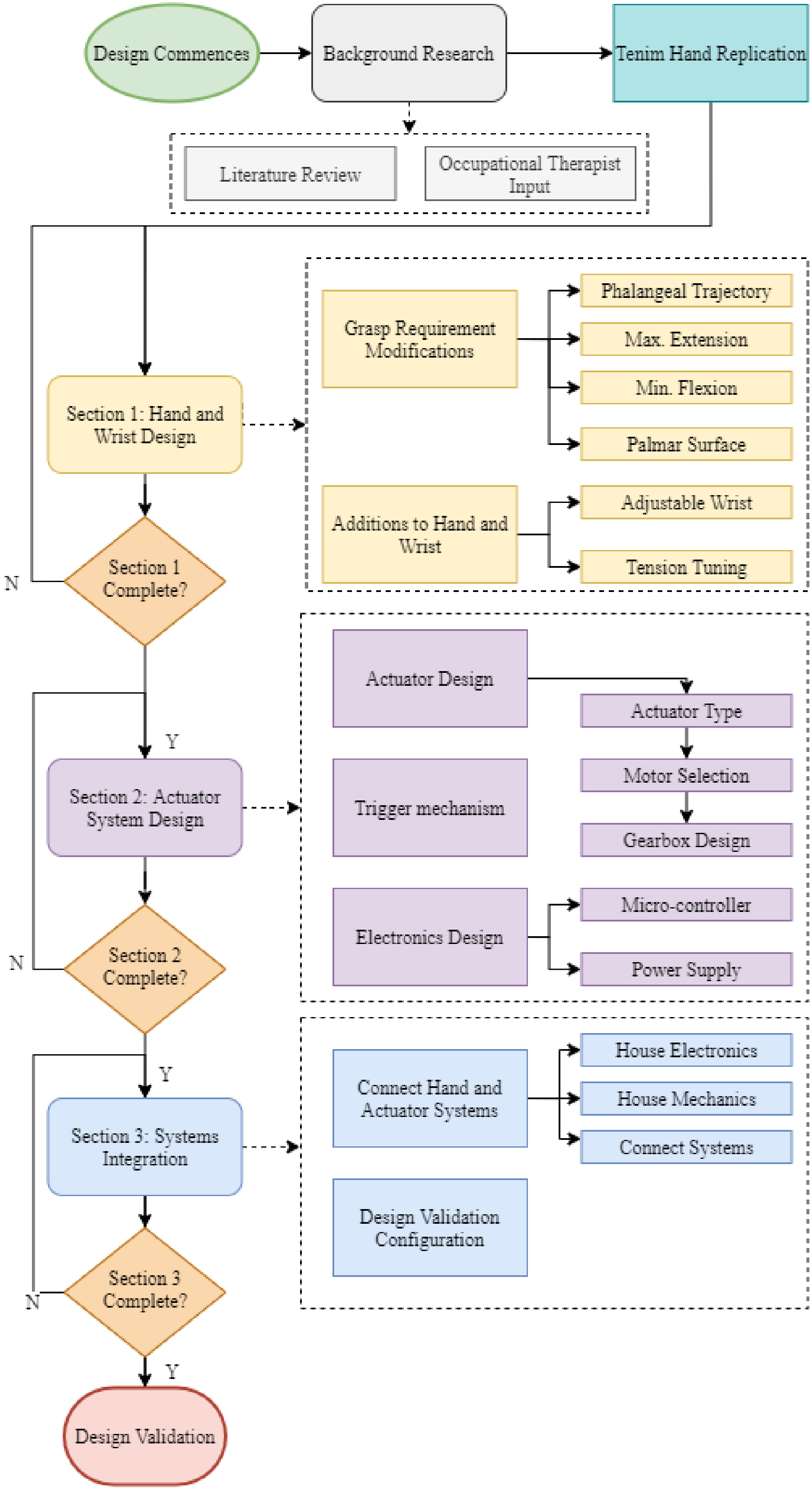


Figure 3.2 Flowchart illustrating the design process followed

3.2 Design Requirements and Considerations

The specifications for the design of the prosthesis were identified and informed through input from an occupational therapist, the patient requirements as found in the literature and the limitations of the original Tenim Hand. The requirements for each section in the design process are as follow:

Section I: Hand and wrist system requirements:

a) Performing the grasps outlined in Table 2-5 with a minimal requirement for object manipulation from the healthy limb.
b) Maintain and improve the anthropomorphism characteristics of the original Tenim Hand.
c) Allow for the adjustment of the tension in the tendon cables connecting the phalangeal components of the Tenim Hand.
d) Allow the user to adjust the wrist through the supinated, pronated and neutral poses of the hand.

Section II: Actuator system requirements:

a) Apply a maximum force of 280N, the maximum rated input force, on the input cable of the Tenim hand (Tenim, 2014).
b) Close/open the hand completely.
c) Hold a grasp passively without effort from the user or requiring continual force application from the actuator system.
d) Require minimal effort to trigger while keeping the healthy limb free to grasp other objects.

Section III: Systems Integration requirements:

a) Integrate the hand and wrist systems with the actuator system
b) Prepare the device for design validation.

3.3 Section I: Hand and Wrist Design

3.3.1 Modification of the Tenim Hand to Meet Grasp Requirements

The original Tenim Hand was capable of a diverse range of different grasps. After replication of the Tenim Hand, it became apparent that while the grasping capabilities of the Tenim Hand was versatile, achieving these grasps often required manual manipulation of both the object being grasped and the prosthesis. Requiring the amputee to manually manipulate objects with their healthy limb greatly diminishes the usefulness of the prosthesis. This deficiency of the Tenim Hand was attributed to three main causes: the degree to which the hand could open, the degree to which the hand could close and the closing trajectory of the phalangeal components of the hand. The requirements to address each of these causes are discussed below.

The closing trajectory of the phalangeal components

The recreated Tenim Hand when grasping has a non-anthropomorphic grasping motion. When the hand undergoes flexion the joints close sequentially from the DIPs to the MCPs. Each joint closes completely before the next joint begins. This results in the distal phalanges of the hand inadvertently pushing away objects that the user is trying to grasp. This phenomenon is illustrated in Figure 3.3. Addressing this phenomenon requires that the hand closes more naturally i.e. sequentially from the MCP to the DIP or with the joints closing simultaneously.

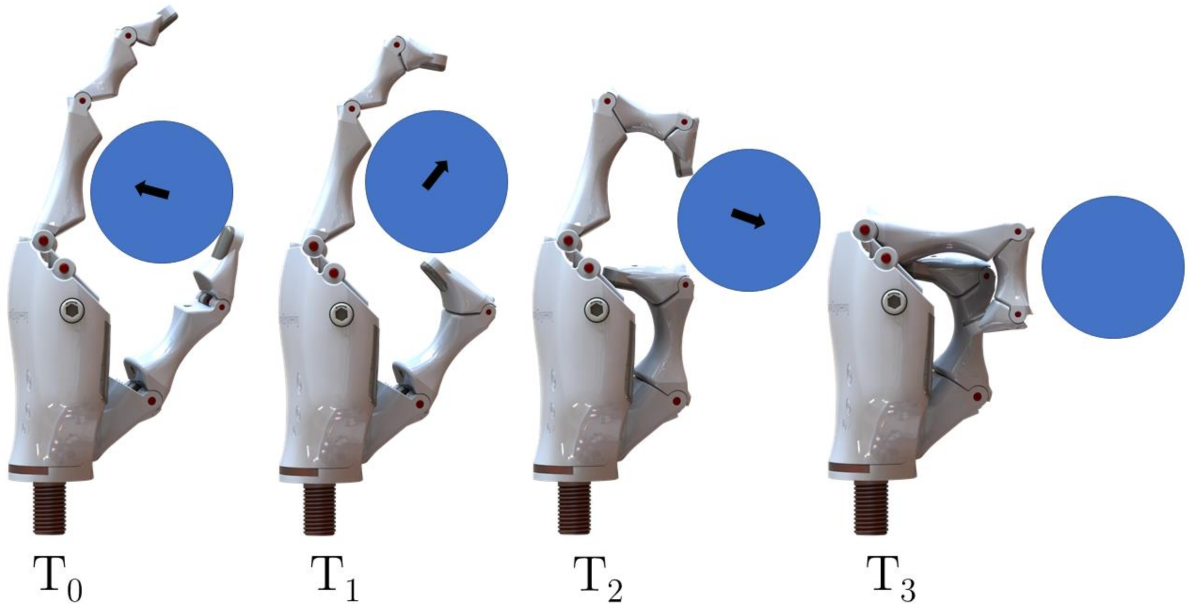


Figure 3.3 Illustration showing how the grasping motion of the original Tenim Hand inadvertently pushes abjects away from its grasp. For this illustration, only the thumb and 3rd Phalanges are shown. The arrow on the object indicates in which direction the object is being pushed.

Maximum Total Extension

The grasping capabilities of the Tenim Hand is restricted by the limited maximum extension that the hand can achieve. The maximum diameter of an object that can be grasped by the hand is approximately 70mm. Improving the grasping capabilities requires that the maximum extension the prosthesis is capable of is increased. Figure 3.4 (A) illustrates how the maximum extension of the Tenim Hand limits the maximum size of the object that can be grasped.

Maximum Total Flexion

Contrasting to the limit of extension, the flexion limitations of the Tenim Hand poses another issue. In maximum flexion, as seen in Figure 3.4 (B), the distal phalanges of the hand do not make adequate contact with the palmar surface. This restricts the minimum size of objects that can be grasped. Increasing the flexion limits, and thereby increasing the contact between the distal phalanges and the palmar surface, will improve the grasping capabilities of the Tenim Hand.

Palmar Surface Curvature

The palm of the human hand has complex curvature. As an approximation, it is curved about both the radio-ulnar and the proximo-distal axes (see Figure 3.5 for an illustration of these axes). However, the palmar surface of the Tenim Hand, as shown in Figure 3.5, is curved about the proximo-distal axis but 'flat' about the radio-ulnar axis. Introducing a concave curvature about the radio-ulnar axis should increase the hand's ability to grasp round objects (especially in a cylindrical grip) by providing more points of contact between the objects and the prosthesis.

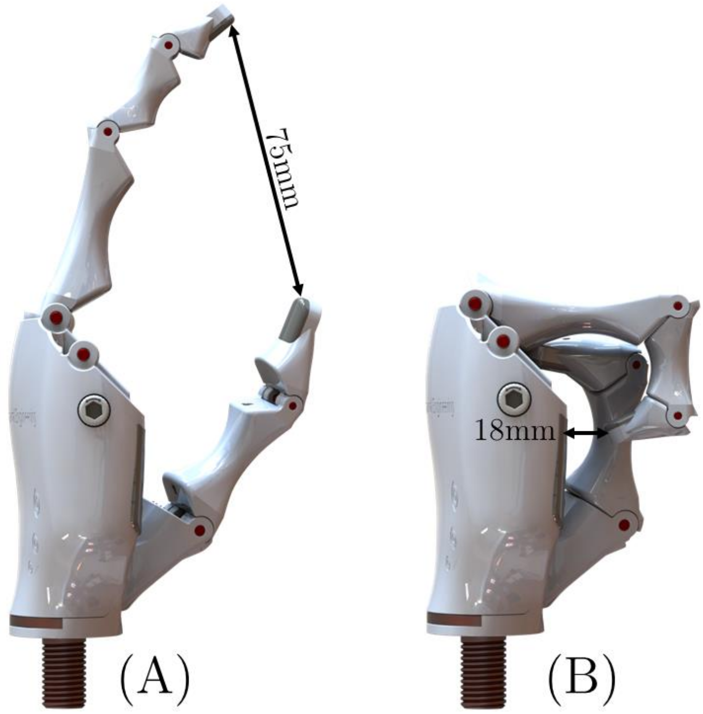


Figure 3.4 Extension (A) and Flexion (B) limits of the Tenim Hand

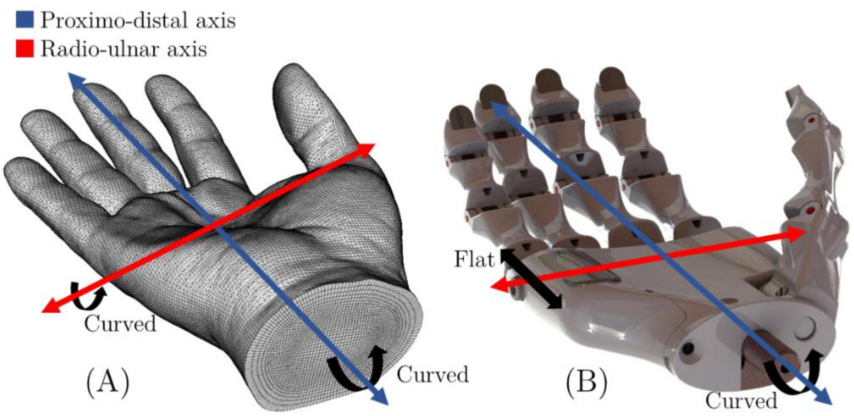


Figure 3.5 Curvature of the palmar surface of the human (A) and Tenim (B) Hands

3.3.2 Wrist adjustment

Consultation with an occupational therapist and evidence in the literature showed that prostheses that had adjustable wrists allowed for greater usability. The requirements listed below were chosen for a prototype wrist mechanism:

- The wrist must have a 180-degree range of motion allowing the hand to be fully supinated or pronated.
- The hand must have three positions in which it can lock: fully supinated; fully pronated; and neutral (90-degrees from both fully supinated and pronated positions).
- Wrist adjustment should allow for one-handed operation using the able limb.

3.3.3 Tension adjustment

Issues were noted in the complexity of assembly of the Tenim Hand. When attaching the tendon cables between the distal phalanges and the internal lever mechanisms of the Tenim hand there is no precise process to ensure that the tendon cable adequately tensions the fingers of the Tenim Hand. This resulted in the fingers either being in partial flexion when the hand was in its neutral state or the fingers having slack and thus would not immediately begin their flexion when the input cable was actuated. The problem is exacerbated when some fingers could be in partial flexion while others were slack. It was proposed that by incorporating a tension tuning mechanism the need for precision when attaching these tendon cables would be greatly reduced. The cables can then be further tuned as the cables lose tension over time. The requirements for the tension tuning mechanism are listed as follows:

- The system must allow for each tendon cable to be individually tensioned.
- Once the cable is tensioned there must be a mechanism for keeping the cable tensioned.
- If the tendon cables slack over time, the system should allow for multiple re-tensionings of the tendon cables.

3.4 Section II: Actuator System Design

3.4.1 Actuator

An actuator is required to reduce the effort required from the user when using the prosthesis. The actuator is used to apply a translational force to the input cable of the prosthesis to induce flexion of the hand. The key requirements and considerations are listed below:

- To exploit the maximum rated input force on the input cable of the Tenim hand, the actuator must apply up to 280N of force.
- The physical size of the actuator must be minimized.
- The actuator should lock in place when not active.

3.4.2 Motor Driver

A motor driver is essential to allow control of the motor in the actuator. The motor driver should meet the following requirements:

- The motor driver should be capable of supplying the voltage and current requirements required for the system.
- Bi-directional control is required for the actuator to induce flexion and allow extension in the prosthesis.

3.4.3 Trigger Mechanism

A means for activating the motor and consequently the hand is required. This trigger mechanism should meet the following requirements:

- The mechanism must allow for the user to select whether the activation mode i.e. extension or flexion.
- It must allow the user to control the extent to which the hand extends/flexes.
- It should leave the able-limb free to hold on to other objects during operation.

3.4.4 Microcontroller Selection

A microcontroller is required to provide the computing power required for controlling the actuator system.

The following requirements for the microcontroller were identified:

- A suitable number of inputs and outputs both digital and analogue must be available for communication between the various components of the actuator system.
- The size of the microcontroller must be minimized for integration into the prosthesis.

3.4.5 Power Supply

A power supply is required to run the various electronics and electromechanical components that are found in the linear actuator system. The requirements for the power supply were identified as follows:

- The power source must be mobile and integrated into the prototype.
- The size of the power supply must be suitable for use in a prosthesis. It must not add significant weight or volume to the prototype.
- The power source must be rechargeable.
- The power source should provide the necessary voltage and current required by the various components of the actuator system.
- The power supply must be forward-compatible for future design iterations that may require additional electronic subsystems

3.5 Section III: Systems Integration

The primary requirement for the systems integration section of the design was to connect the hand and wrist systems with the actuation system. The two secondary requirements for the systems integration include housing the electronic and mechanical components of the prosthesis and making any necessary adaptations that may be required for the design validation process (e.g. testing rigs and mounting points for testing).

4 Design Outcomes

In this chapter, the outcomes of the design process are presented. The evolution of the prototype from a body-driven prosthesis in the Tenim Hand to the electromechanically actuated prototype used in the design validation chapter is presented through the meeting of the design considerations. Rapid prototyping principles and techniques were followed to produce most of the parts used for the prototype.

4.1 Section I: Hand and Wrist

This section highlights the modifications made to the Tenim Hand to rectify the grasping deficiencies of the original version and describes the novel additions of the tension tuning system and the wrist adjustment mechanism.

4.1.1 Tenim Hand Modifications

Closing Trajectory of the Fingers

The closing trajectory of the modified Tenim Hand was adjusted to allow the phalanges to follow a more natural trajectory than that of the recreated Tenim Hand. This was achieved by reducing the strength of the torsion springs, shown in Figure 2.2, of the MCP and PIP joints. The tolerance between the phalanges and the joint pins were also increased to reduce friction thus also aiding in the rotation of the proximal and intermediate phalanges. The new closing trajectory of the modified Tenim Hand is illustrated in Figure 4.1.

Increase in Range of Motion

The range of motion in the original Tenim Hand was limited both in flexion and extension. This restricted both the maximum and minimum sizes of objects that could be grasped. This was remedied by increasing the size of the joint angles of the phalanges. Figure 4.2 shows the increased range of motion in the modified Tenim Hand when compared to that of the original.

Under the maximum extension, see Figure 4.2 (2-A), the long axes of the 2nd to 5th phalanges are now parallel to the palmar plane, whereas the long axes of the 1st phalanges are almost perpendicular to the palmar plane. The increased extension capabilities allow the modified Tenim Hand to grasp larger objects than that of the original.

Under maximum flexion, see Figure 4.2 (2-B), the distal phalanges now make contact with the palmar surface. Palmar contact with the phalanges allows the modified Tenim Hand to grasp smaller objects than the original Tenim Hand and improves the stability of grasps involving larger objects that were on the lower limit of the original Tenim Hand's grasping capabilities.

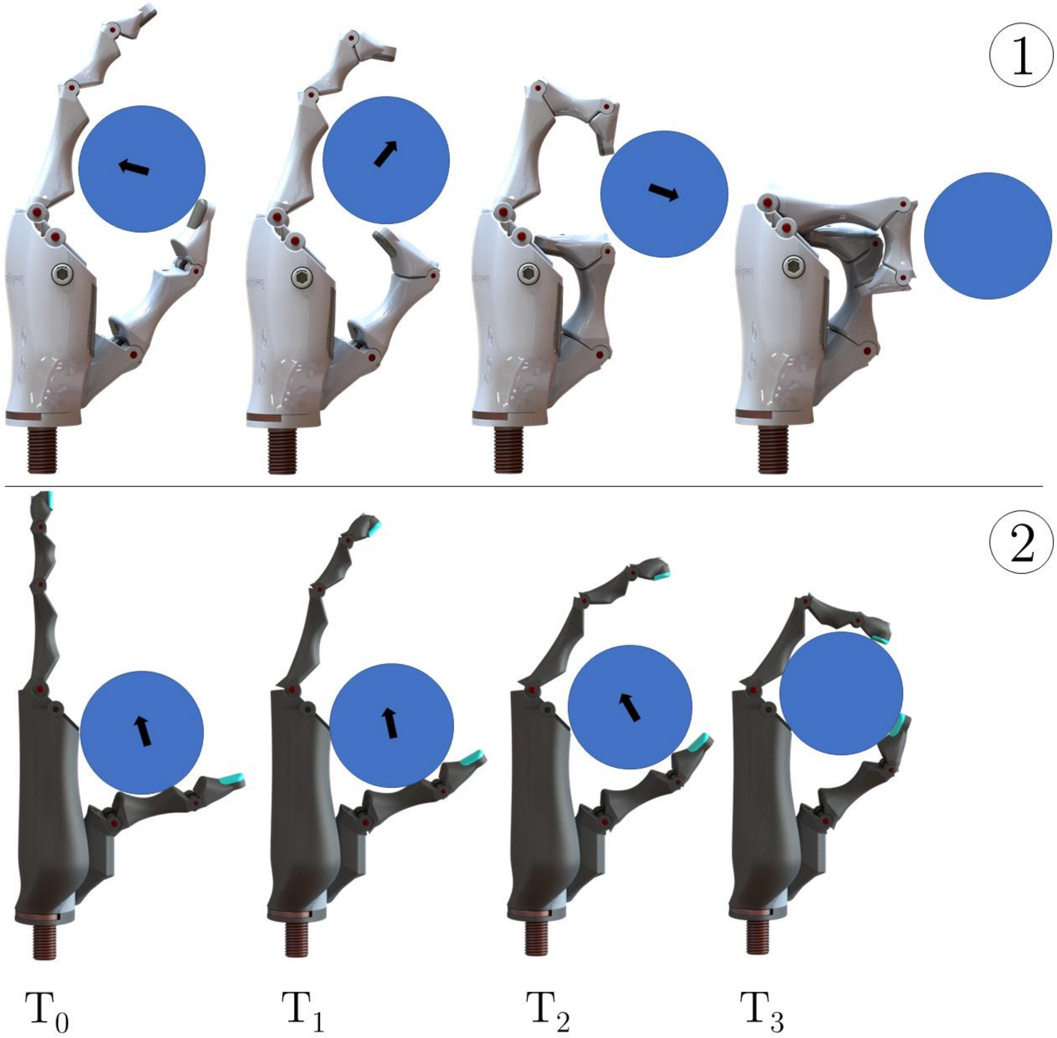


Figure 4.1 Illustration showing the more natural grasping trajectory of the modified Tenim Hand (2) and how it aids in the grasping of a cylindrical object when compared to the Tenim Hand (1). For this example, only the thumb and 3rd Phalanges are shown. The arrow on the object indicates in which direction the object is being pushed.

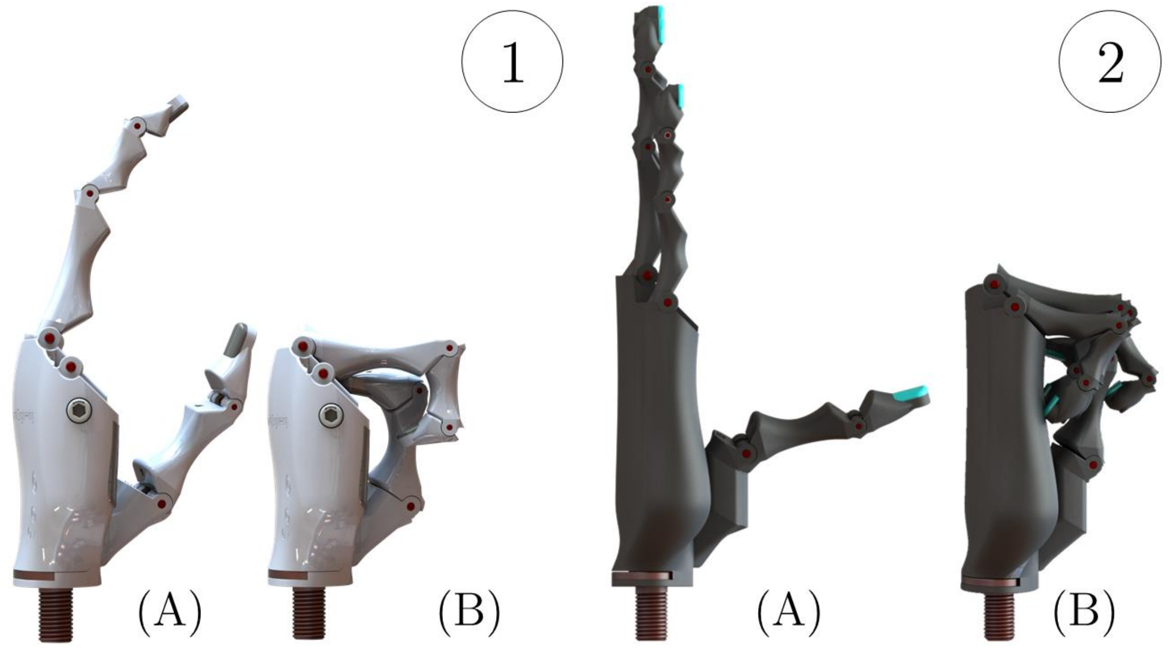


Figure 4.2 Comparison of the extension (A) and flexion (B) limits of the Tenim Hand (1) and the modified Tenim Hand (2).

Palmar Surface

The curvature of the modified Tenim Hand's palmar surface was increased slightly about the proximo-distal axis, however, the amount of curvature added was limited by the spacing requirements of the internal components. The curvature introduced a 'cup' to the palm that is expected to aid in the grasping of objects by increasing the number of contact points a grasped object has with the hand.

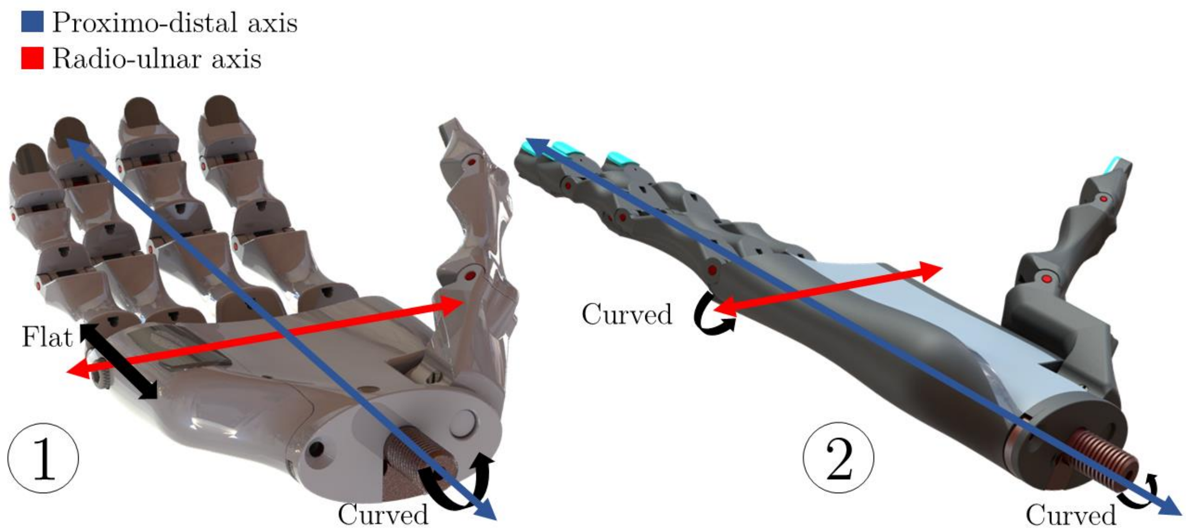


Figure 4.3 Comparison of the palmar surface curvatures of the Tenim Hand (1) and the modified Tenim Hand (2).

Internal Components of the Tenim Hand

The internal components of the original Tenim Hand, see Figure 2.5, played very little role in its deficiencies, thus, barring the linear bearing rail and the ratchet locking mechanism, they remain mostly unchanged in the new prototype. The linear bearing rail was lengthened by 20mm to accommodate the increased range of motion of the modified Tenim Hand. The ratchet locking mechanism was deemed redundant by the requirement for the actuator to lock in place when not active and was subsequently removed from the new design.

Tension Tuning Mechanism

The tension tuning mechanism is incorporated into the 2nd to 5th digits and comprises a tension reel (see Figure 4.4 (A)), a modified distal phalanx and a grub screw. The tension cable is first threaded through the tension reel and then threaded through the phalanges of the digits before it reaches its terminus at the differential levers (see 2.1 The Tenim Hand). Once the cable is fastened the tension reel can be wound with a standard screwdriver to remove any slack in the cable. Once suitably wound, the reel is locked into place using a grub screw. Should the cable begin to slack, the grub screw can be loosened and the reel re-wound. Figure 4.4 (B) shows a cross-section of the tension tuning mechanism.

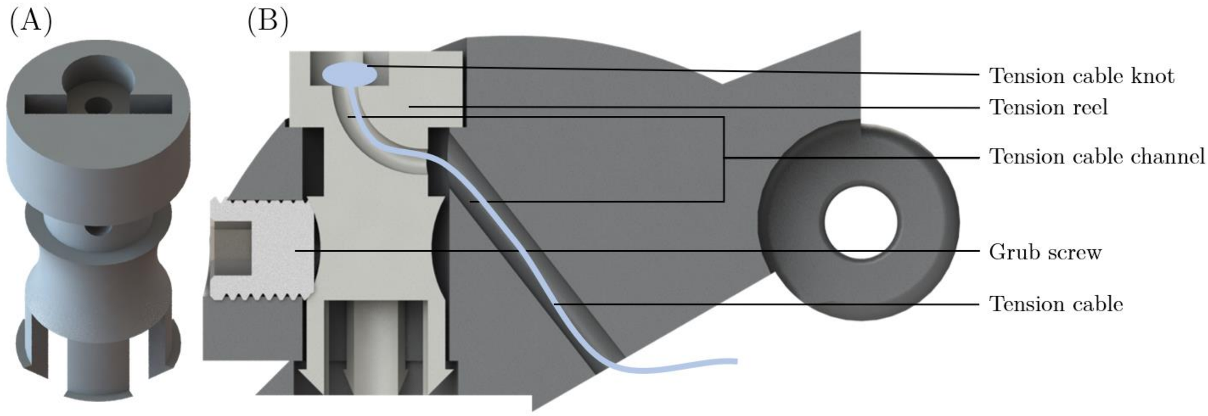


Figure 4.4 (A) The tension reel. (B) Cross-section of tension tuning mechanism and its components.

4.1.2 Wrist Adjustment Mechanism

The wrist adjustment mechanism was added to the modified Tenim Hand to mimic the pronation and supination capabilities of the human hand thereby increasing the functionality of the device. Figure 4.5 shows an exploded view of the components that make up the wrist mechanism. The system uses a spring-loaded latch that can slip into one of the three distinct slots of a slotted cylinder fastened with a grub screw to the attachment plate. When the latch is released through user action the slotted cylinder can rotate. If the user is no longer holding the latch open, the latch will be pushed by the spring into the cylinder. The wrist can then still be rotated until one of the slots aligns with the latch. The latch is then pushed into the slot and the wrist is then locked into place. The wrist can be locked in three positions, namely: pronated, neutral and supinated, with 90-degree offsets between them. There is a boss on the rim of the slotted cylinder that slides in a groove on the underside of the latch housing (both not shown in the view from Figure 4.5) that prevents the wrist from over-rotation ensuring that the wrist cannot be moved straight from being supinated to be pronated or vice versa. Figure 4.6 shows the three locking and two transitional phases when moving the wrist from pronated to supinated.

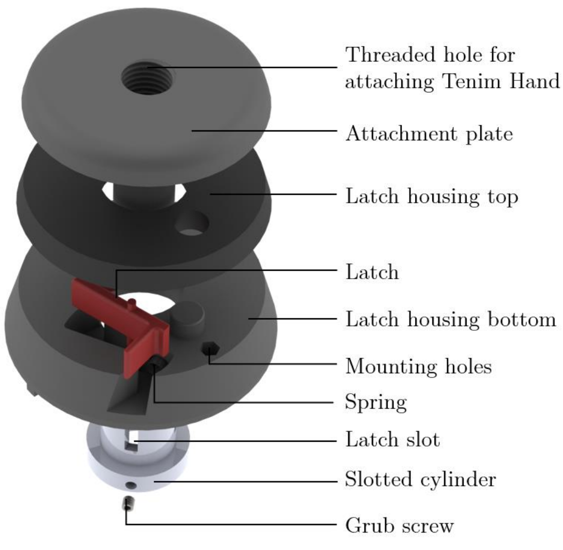


Figure 4.5 Exploded view of the components of the wrist adjustment mechanism

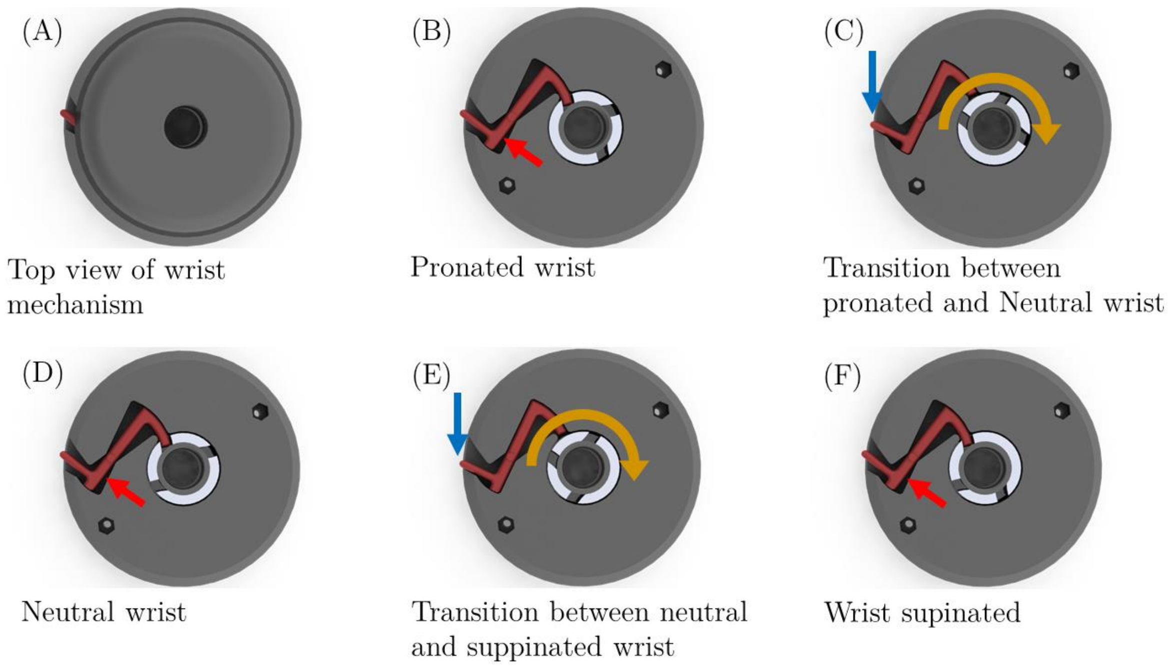


Figure 4.6 (A) Top view of the assembled wrist mechanism. (B-F) Shows the wrist moving from being pronated (B) the latch is then released and the wrist is rotated (C) until it is locked into the neutral position (D). The latch is then released again and rotated (E) until it is in the supinated position (F). (The red arrow indicates the spring pushing the latch into the cylinder, while the blue and yellow indicates user latch release and user rotation respectively)

4.1.3 The Modified Tenim Hand with Wrist

The modified Tenim Hand with the wrist adjustment mechanism is shown assembled in different phases of wrist rotation in Figure 4.7.

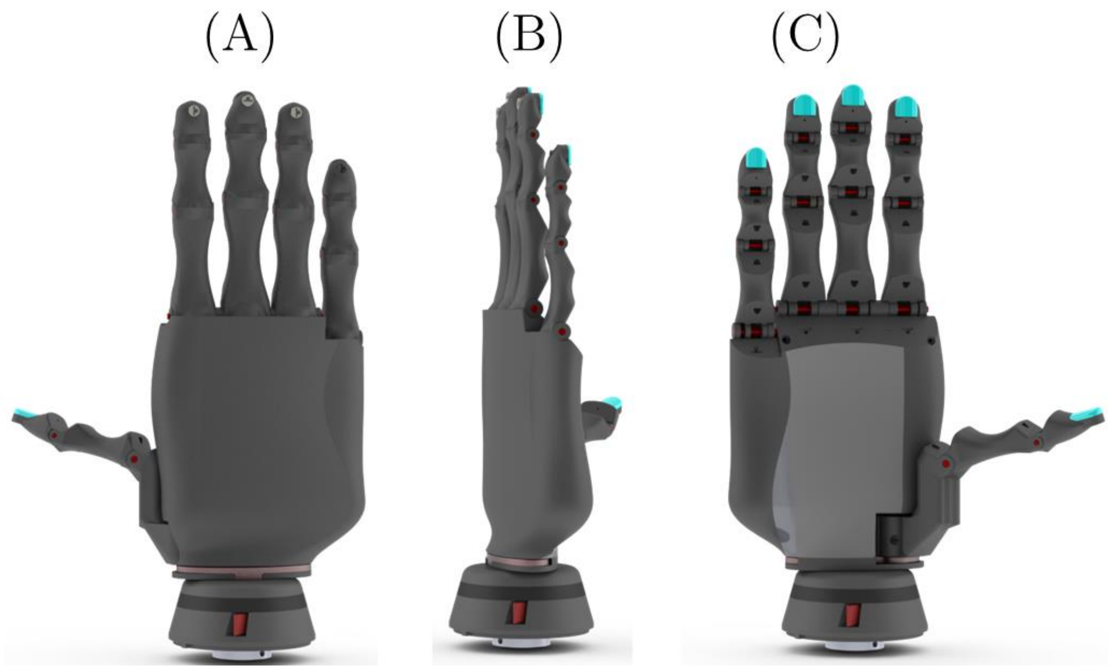


Figure 4.7 The modified Tenim Hand in the pronated (A), neutral (B) and supinated (C) positions.

4.2 Section II: Actuation System

This section highlights the development of the linear actuator system and its associated electronic and mechanical subsystems.

4.2.1 The Actuator

Although there are many commercially available linear actuators, it was decided that to meet the unique force and size requirements of the actuator system a custom actuator would be built. The actuator, shown in Figure 4.8 (A), comprises a DC motor, a single-stage gearbox (highlighted in Figure 4.8 (B)), two radial bearings, a lead screw and nut, a screw endcap and two limit switches. When a voltage is applied to the motor the attached drive gear rotates drives a larger gear thereby reducing the speed and increasing the torque. The larger gear is fixed to a radial bearing's inner ring on one end and the lead screw nut on the other. When the larger gear is driven, the lead screw nut, attached to the inner ring of the other bearing, induces linear motion on the lead screw. For a positive voltage on the motor, the lead screw will be extracted out of the housing and for a negative voltage, the lead screw will be retracted into the housing. The lead screw is prevented from over-extraction or over-retraction by the attached lead screw end cap tripping the limit switches which in turn stops the motor driver from providing power to the motor.

The approach chosen for the design of the linear actuator was to select affordable off the shelf components for the components that would be most complex to manufacture, i.e. the lead screw and DC motor, followed by designing a gear reducer to ensure the actuator as a whole meets the requirements set in chapter 3.4.1.

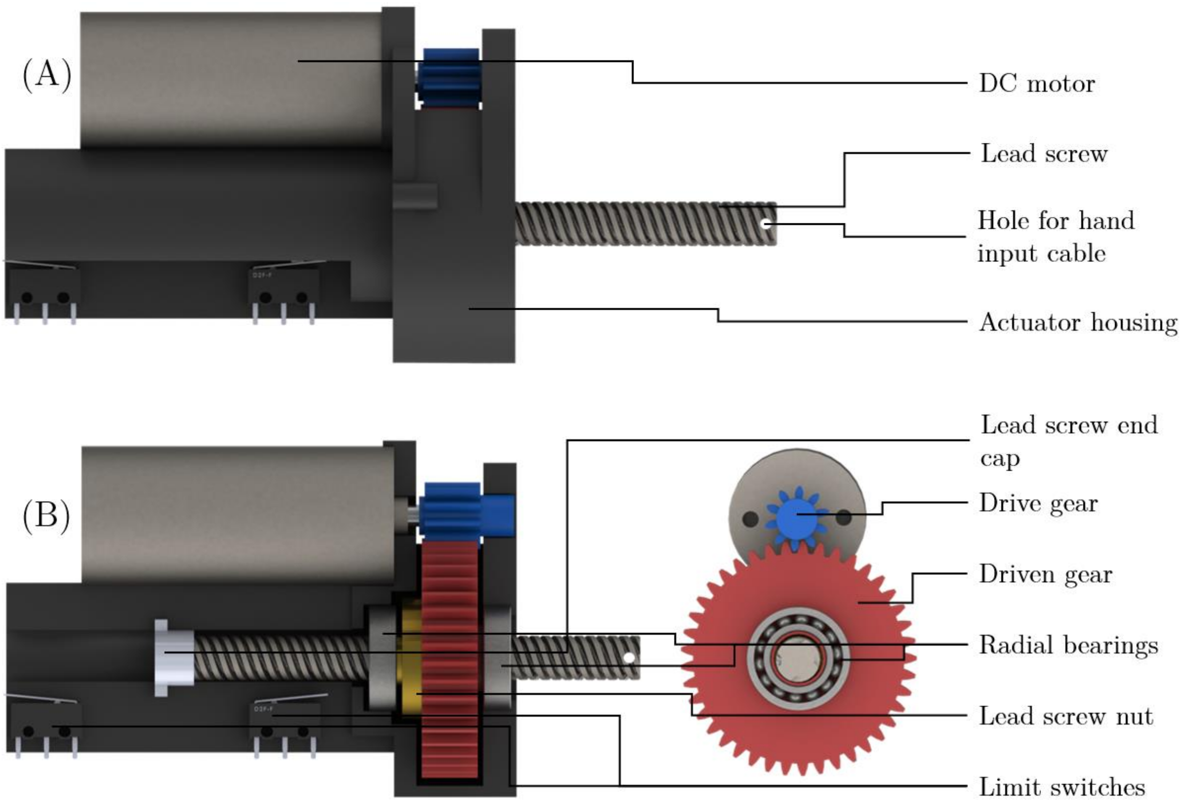


Figure 4.8 (A) The linear actuator. (B) The linear actuator is shown with the housing cross-sectioned next to a side view of the actuator without the housing.

Lead Screw and Nut Selection

A lead screw was required to convert the rotation of the motor shaft to linear motion. The lead screw and nut selected for the actuator system has an 8mm diameter with a lead and pitch of 8mm and 2mm respectively. The lead screw and the nut are made of hardened stainless steel and brass respectively. The lead screw was primarily chosen for its relatively small diameter combined with its relatively large lead ensuring that the screw would not negatively affect the size of the actuator while also providing the linear translation required. Table B-1 in Appendix B lists the lead screw and nut specifications.

Motor Selection

The motor selected is the high-torque DAGU Wild Thumper Motor 75:1. The motor has a built-in 75:1 gearbox resulting in a stall torque of 7.4kg.cm (726 N.mm) at a stall current of 3.4A. The no-load current is 0.35A and is rated for a nominal input voltage of 6V. The motor is 25mm in diameter and 69.5mm long. Table B-2 in Appendix B lists the DAGU Wild Thumper Motor's specifications.

Figure 4.9 DAGU Wild Thumper Motor 75:1 (DaguRobot, 2020)

Gearbox design

The gearbox was designed by calculating the ratio between the torque output of the motor, $T_{M,}$ and the torque required, T_R, to raise a load of known magnitude, F, with a lead screw of known specifications. Table 4-1 lists the specifications that are relevant to the calculations needed to design the gearbox. The gear module was selected as $m = 1$.

Table 4-1 Known specifications required for the gearbox design calculations.

Specification	Value
Load, F [N]	280
Friction coefficient, µ	0.2
Thread angle, 2α [°]	30
Lead, l [mm]	8
Mean diameter, d_m	7.25
Motor Torque, T_m [N.mm]	726

To calculate T_R the following equation was used (Budynas & Nisbett, 2015):

$$T_R = \frac{Fd_m}{2}\left(\frac{l + \pi \mu d_m sec\alpha}{\pi d_m - \mu l sec\alpha}\right)$$

Using the specifications in Table 4-1 we find that:

$$T_R \approx 2{,}860\ N.mm$$

Using the motor torque T_m and T_R, the desired gear ratio, $GR_{Desired}$, can be found using the gear ratio formula:

$$GR_{Desired} = \frac{T_R}{T_m}$$

$$GR_{Desired} \approx 4$$

To ensure wear across the teeth of the gears is an even, a coprime ratio of 41 teeth on the driven gear and 10 teeth on the drive gear was selected. The resultant gear ratio is calculated as:

$$GR_{actuator} = \frac{N_{driven}}{N_{drive}}$$

$$GR_{actuator} = \frac{41}{10} = 4.1 \approx 4$$

$$\therefore GR_{actuator} = GR_{Desired}$$

The specifications for the gearbox derived above are listed in Table 4-2.

Table 4-2 Specifications of the designed gearbox

Specification	Value
Drive gear teeth, N_{drive}	10
Driven gear teeth, N_{driven}	41
Gear ratio, $GR_{actuator}$	4.1
Module, m	1

Other actuator components

Radial bearings, limit switches and a lead screw end cap were used to provide various functionalities and features to the actuator. Table 4-3 lists the functions and specifications of these components.

Table 4-3 Additional components of the linear actuator, their function, and their specifications

Component	Qty.	Function	Specifications
Radial bearing	2	Reduces rotational friction on the driven gear and lead screw end cap	Inner diameter: 12mm Outer diameter: 20mm
D2F-F limit switch	2	Prevents over-extraction and over-retraction of the lead screw	Single-pole double-throw switch
Lead screw end cap	1	Prevents rotational motion of lead screw and activates limit switches under full extraction and retraction	NA

4.2.2 Additional Electronics and Actuator Control

Trigger Mechanism

The trigger mechanism designed for the actuation system was designed with simplicity and robustness in mind. The trigger mechanism comprises two DTS25N momentary pushbutton switches wedged between two curved plates that are hinged together (as illustrated in Figure 4.10). The DTS25N has an activation force of 160gf (1.57N). The bottom plate includes a slot that contains a strap for attaching the mechanism to the body. The mechanism is to be placed underneath the able-limb (as shown in Figure 4.11). By pushing on either side of the hinge with the underside of the able limb one of the two pushbutton switches is activated thereby indicating to the microcontroller whether the user intends to flex or extend the prosthesis. The user is still able to grasp objects using the able limb during this process. It is believed that through using this simple trigger mechanism the training required to operate this device when compared to myoelectric devices will be minimised, however, assessing this claim is beyond the scope of this dissertation.

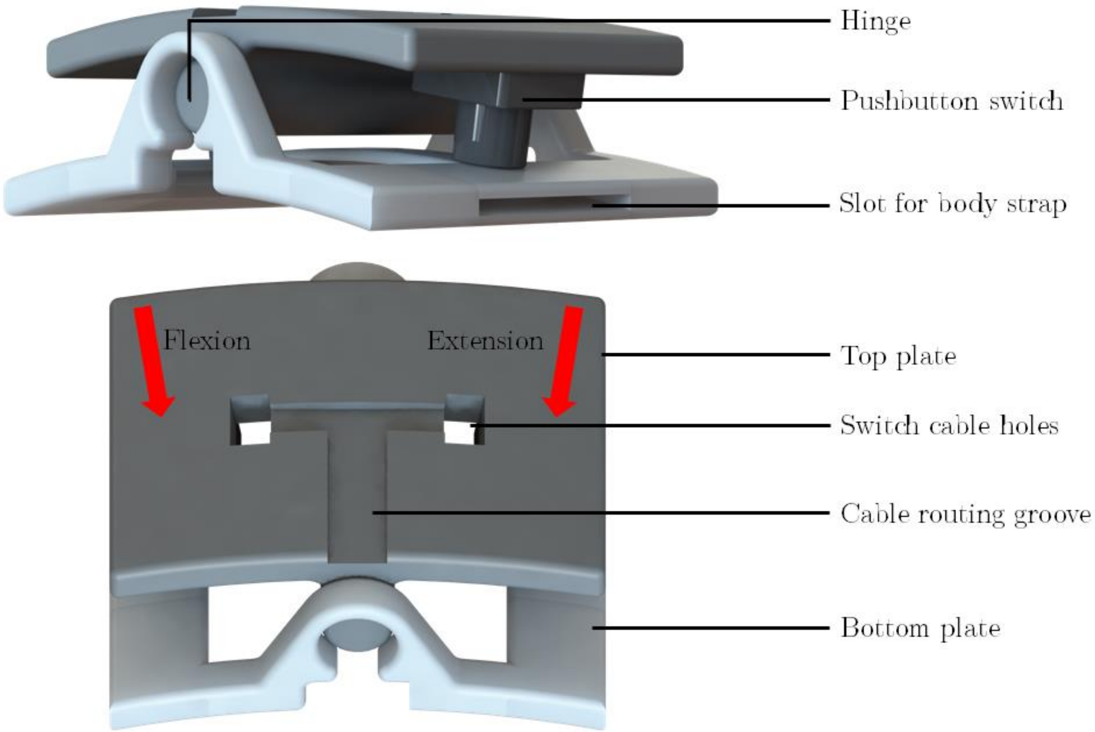


Figure 4.10 The elements and components of the trigger mechanism

Figure 4.11 Placement of trigger mechanism underneath the able limb.

Microcontroller

An Arduino Nano, shown in Figure 4.12, was selected to provide the computing power required by the actuator system. The Nano was chosen for its compact package and provided sufficient input and output (IO) pins, including pulse-width modulated (PWM) outputs, for the system (see Table 4-4). The Nano also includes an onboard 5V voltage regulator that negates the need for additional regulator circuitry. Table B-3 in Appendix B shows the specifications of the Arduino Nano.

Table 4-4 Arduino Nano IO and system IO requirements

	Arduino IO	System Requirements
Digital IO	22	4
Anologue Input	8	1
PWM Output	6 (shared with Digital IO)	1

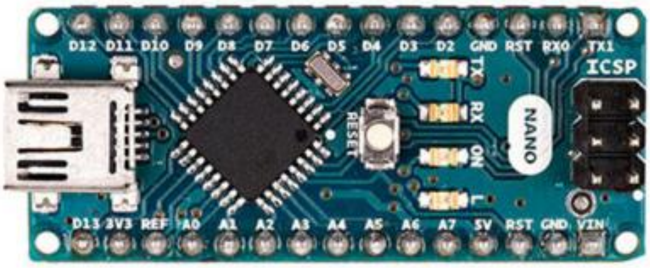


Figure 4.12 The Arduino Nano (Arduino, 2020)

Motor Driver Selection

The motor driver selected is the Monster Moto Arduino shield, shown in Figure 4.13, based on the VNH2SP30 motor driver integrated circuit. The Monster Moto, made for Arduino development boards, allows for high current outputs in a relatively small package. The driver also includes thermal, overvoltage and undervoltage shutdown safety features and has protection diodes integrated into the circuit board. Table B-4 in Appendix B shows the relevant specifications of the Monster Moto.

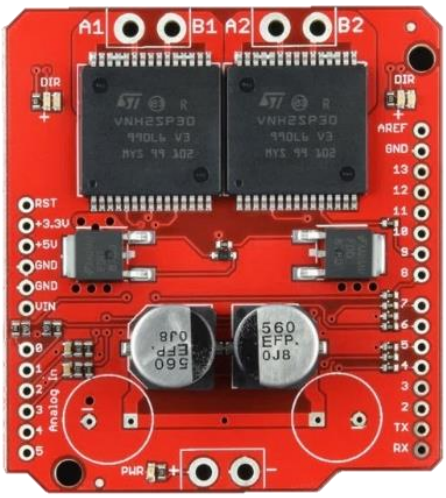


Figure 4.13 The Monster Moto Arduino shield (Sparkfun, 2020)

Power Supply

A power source is required to supply the electrical energy required by the actuator system. The power supply needs to provide power for the DC motor, microcontroller and the motor driver. Table 4-5 shows the power requirements of the different components of the system.

*Table 4-5 The power requirements for the powered components of the actuator system. *Note that the DC motor is supplied through the motor driver effectively limiting the supply voltage of the motor driver to 6V-7.5V. ** The listed current does not include the current that the motor will draw through the motor driver.*

Component	Supply Voltage[V]	Max Current Draw[mA]
Microcontroller	7-12	200
DC Motor	6-7.5	3,400
Motor driver	5.5-16*	20**

The component requiring the highest minimum supply voltage is the Arduino Nano which requires a minimum of 7V. The component with the highest maximum supply voltage is the DC motor at 7.5V. The current requirement under maximum load for the power supply is 3,620 mA. With these requirements in mind the Ansmann 7.4V li-ion battery, shown in Figure 4.14, was chosen for supplying the system.

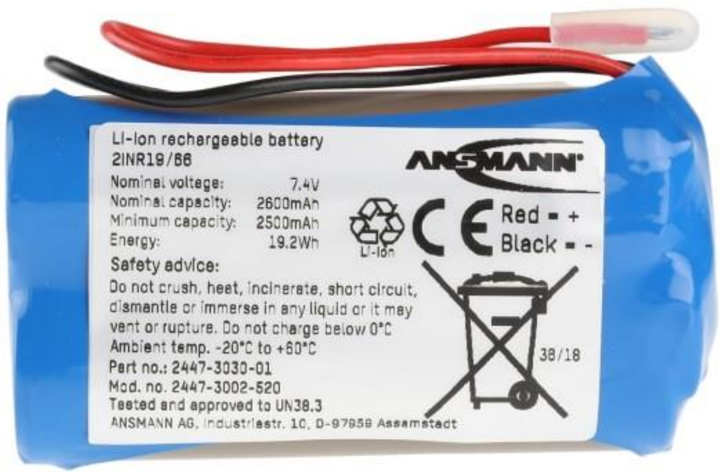


Figure 4.14 Ansmann 7.4V Li-ion battery

The battery has a nominal and a maximum charged voltage of 7.4 and 8.6V respectively and has a maximum discharge current of 5,000mA. While 8.6V is above the maximum rated voltage the DC motor can be operated at, by placing a diode with a

1.1V drop off in series with the motor driver, and therefore the motor, the maximum voltage as seen by the motor is limited to 7.5V - the upper limit of the motor's rating. The diode also provides reverse voltage protection to the system. The specifications for the battery are shown in Table B-5 in Appendix B. A rocker switch was also added to turn the system on or off.

Control Approach

For this prototype a simple open-loop control approach was adopted, however, future prototypes may require a closed-loop approach. In the open-loop approach, the user applies a force onto the trigger switch which in turn converts the user action to a digital electric signal. The force applied should exceed the 160gf (1.57N) activation force of the DTS25N switches plus the friction of the hinge. The signal is detected by the microcontroller which calculates the appropriate control action. The control action is then sent as digital directional and PWM signals to the motor driver which then provides the required voltage to the motor. The rotational motion of the motor is converted to linear motion in the lead screw and correspondingly into the input actuation cable of the Tenim Hand. Through the lever and pulley systems embedded in the hand, this force is translated into the grasping force of the hand. Ultimately the degree to which the hand opens or closes depends on how long the user activates the trigger mechanism. This open-loop system is illustrated in Figure 4.15.

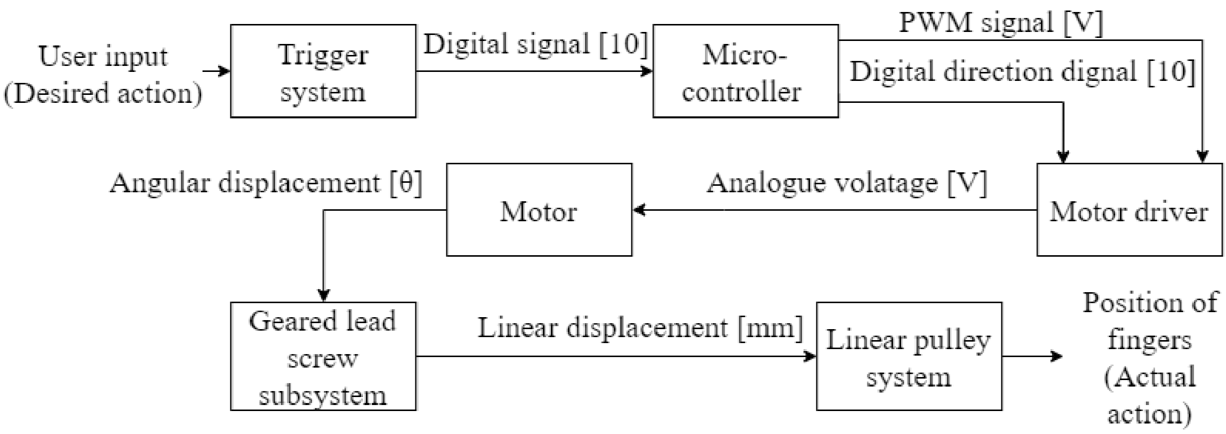


Figure 4.15 Open-loop control approach

Circuit Diagram

Figure 4.16 shows the full circuit diagram used in the actuator system.

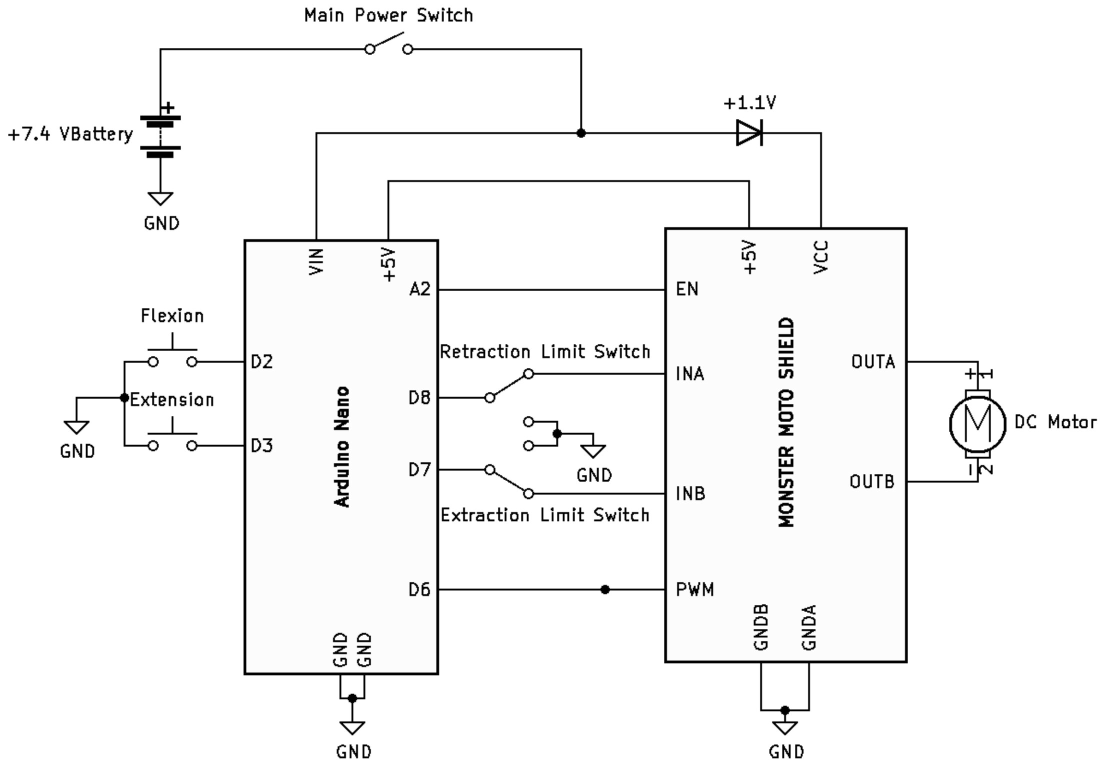


Figure 4.16 Circuit diagram for the actuator system. Only the pins used on the Arduino Nano and Monster Moto Shield are shown.

4.3 Section III: System Integration

This section highlights the integration of the modified Tenim Hand and wrist with the actuation subsystem to form the Self Actuated Tenim Hand (SATH). The systems integration included: providing housing for the components of the actuator system; connecting the actuator systems to the hand and wrist; attachments for allowing the SATH to undergo design validation.

4.3.1 Actuator Housing

The actuator housing was designed to house and protect the battery, actuator, motor driver and microcontroller in a space-efficient manner. As shown in Figure 4.17, the greatest contributor to the volume of the actuator system is the actuator. The microcontroller, motor driver and battery do not add additional length to the system and make only minor contributions to the width.

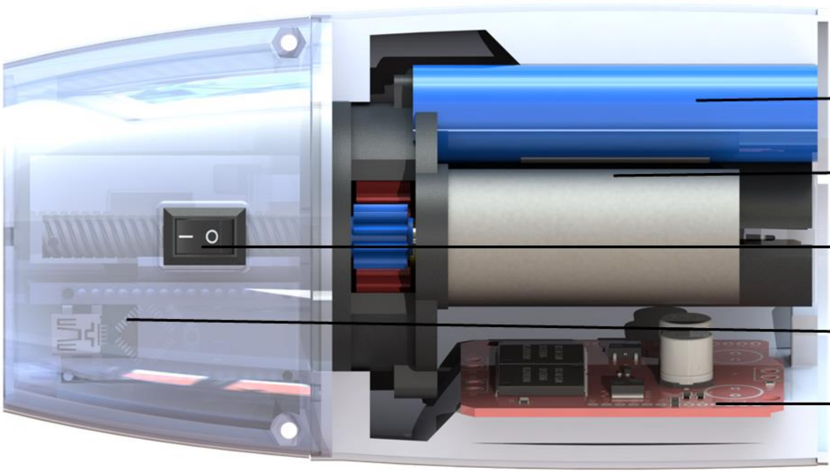


Figure 4.17 The components of the actuator system shown in their mounted positions in the actuator housing (wires and cabling not shown)

4.3.2 Connecting the Actuator System to the Hand and Wrist

The actuator housing and the wrist were designed with systems integration in mind. The assembled SATH is shown in Figure 4.18 (A). The section views of Figure 4.18 (B) and (C) shows the actuator system controlling the movement of the hand.

4.3.3 Design Validation Prototype

The attachment for the SATH shown in Figure 4.19 was designed for the SATH to undergo design validation without the participation of amputee subjects. The attachment allows the researchers to complete ADLs and other activities with the SATH so that any potential shortfalls with the hand may be corrected before later validating the device in pre-clinical and clinical trials.

The SATH shown in Figure 4.20 was used for the design validation discussed in subsequent chapters. Figure 4.20 (A) shows the fully assembled SATH with the attachment in place. The internal components of the SATH are shown in Figure 4.20 (B). The attachment fixes the SATH to the arm using straps as shown in Figure 4.20 (C).

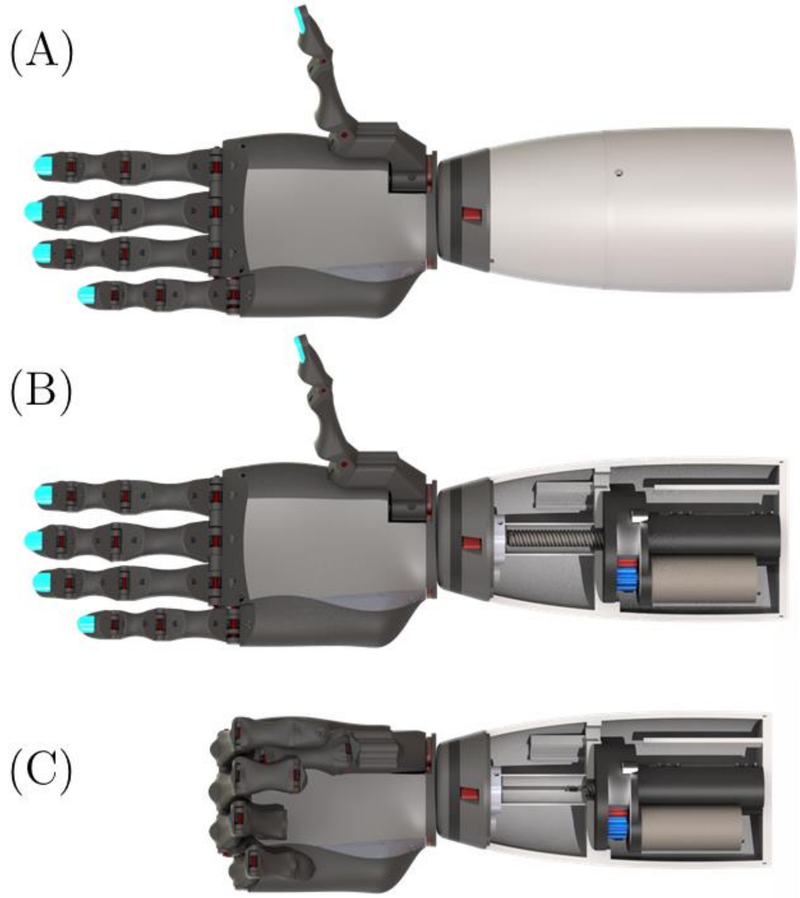


Figure 4.18 (A) The fully assembled SATH. (B) The assembled SATH fully extended with the actuator housing sectioned. (C) The assembled SATH fully flexed with the actuator housing sectioned. Note the linear translation of the lead screw between (B) and (C)

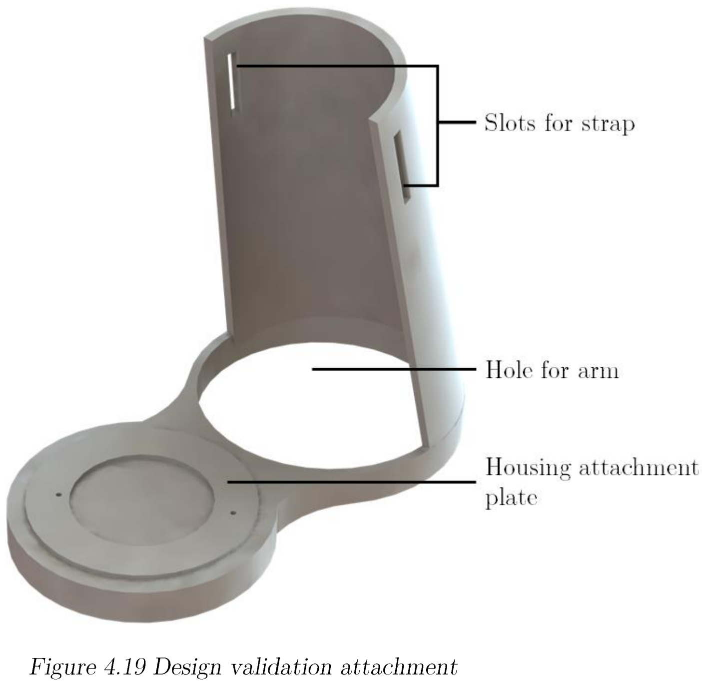


Figure 4.19 Design validation attachment

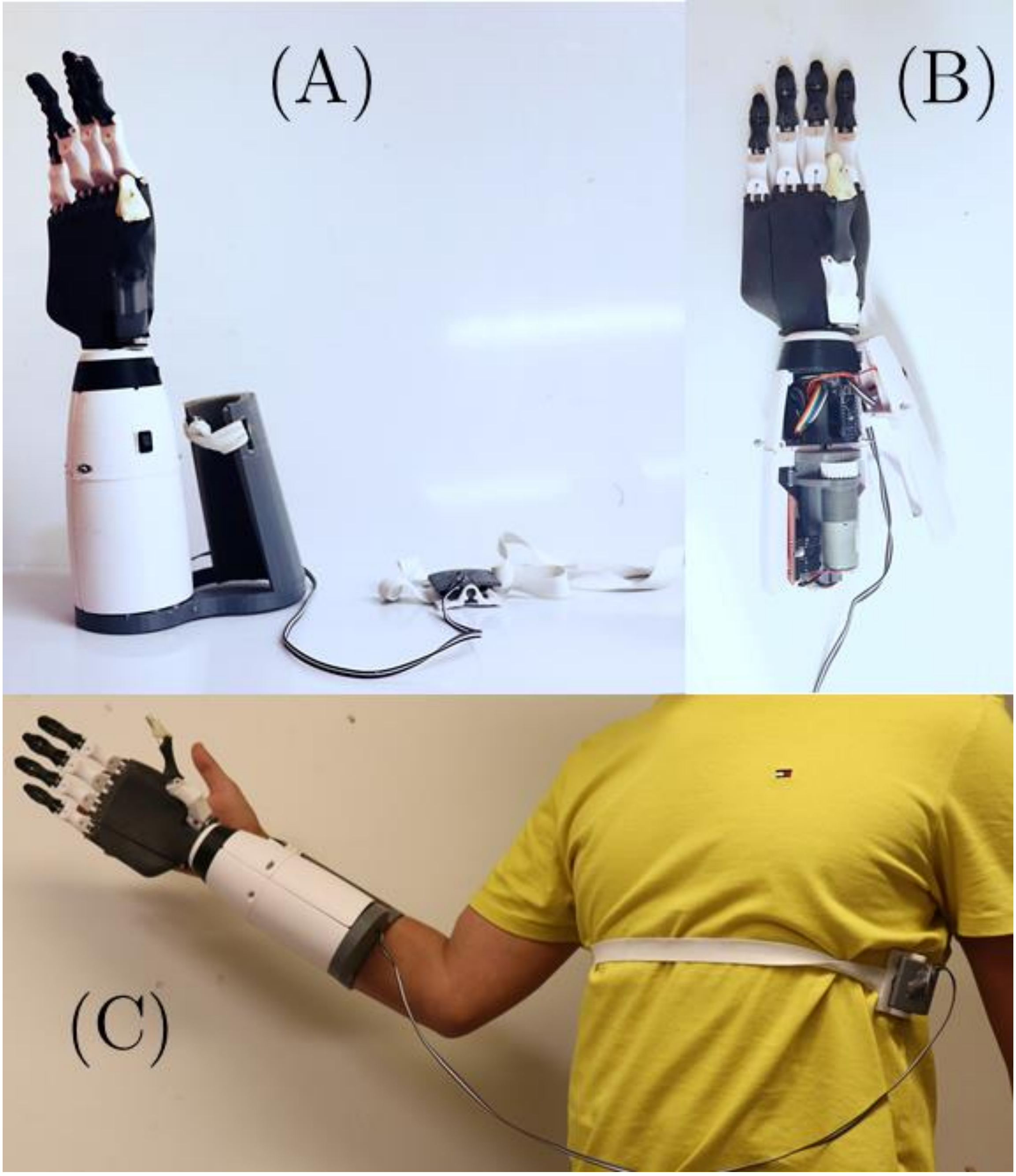


Figure 4.20 (A) The SATH with the attachment for design validation attached. (B) An internal view of the design validation prototype of the SATH. (C) The SATH being fixed to a healthy limb using the design validation attachment.

5 Design Validation

In this chapter, the experimental methodology for the design validation of the SATH is discussed. In Chapter 2 both SHAP and AHAP were discussed as potential means for assessing hand function. Ultimately, AHAP was selected as the preferred assessment due to the easier access to the equipment required and the assessments focus on the assessment of prosthetic hand function.

As this validation process is preliminary to further design, the researcher used the design validation attachment to perform the tasks required by AHAP. Once the performance of the prostheses is deemed acceptable pre-clinical studies can be completed using amputee participants, at which point usability and other user-dependent factors such as ergonomics can also be assessed.

5.1 Experimental Setup

The experimental procedure for AHAP requires the utilisation of 25 different objects that are used to complete 26 different tasks (Llop-Harillo et al., 2019). The tasks are divided into 8 different grasp types and two non-grasping postures. The objects used in AHAP should be sourced from the Yale-CMU-Berkeley Object and Model Set (YCB), however, for this study, due to funding and timing considerations, the objects that were used were sourced independently. The sourced objects were selected to imitate the characteristics of both the weights and size of their YCB counterparts as far as practicable. Table 5-1 below shows the different objects being used in the experiment grasped using the desired grasp type for each specific task.

Table 5-1 Grasp types and images showing the desired grasp for each Task adapted from Llop-Harillo et al. (2019)

Grasp Type	Objects and Task No.		
Hook (H)	T_{01} – skillet lid 	T_{09} – pitcher base 	T_{19} – Rope with weight 
Spherical grip (SG)	T_{02} – apple 	T_{11} - softball 	T_{20} – mini soccer ball 
Tripod pinch (TP)	T_{03} – large marker 	T_{12} – tuna can 	T_{21} – golf ball 
Extension grip (EG)	T_{04} - plate 	T_{13} – cracker box 	T_{22} – pudding box 
Cylindrical grip (CG)	T_{05} – chips can 	T_{14} – coffee can 	T_{22} – power drill 

Table 5-2 Grasp types and images showing the desired grasp for each Task adapted from Llop-Harillo et al. (2019) *(continued)*

Diagonal volar grip (DVG)	T_{06} –screwdriver 	T_{15} – spatula 	T_{24} – skillet 
Lateral pinch (LP)	T_{07} - bowl 	T_{16} – XS clamp 	T_{25} – key 
Pulp pinch (PP)	T_{08} - pear 	T_{17} – small marker 	T_{26} – small washer 
Index point (IP)	T_{09} - timer 		
Platform (P)	T_{18} - plate 		

5.2 Procedure

The procedure outlined below was followed to perform AHAP. Steps 4 and 5 below are scored based on the scoring system presented in

Table 5-3. The SATH was used to grasp each object listed in Table 5-1 in the order of their task number.

1. The object is presented and shown the correct grasp or task for completing the task. (Table 5-1 shows the correct grasp for each object)
2. The subject practices the grasp for one minute.
3. The object is held over the hand of the subject while the subject's hand is positioned so the palm is pointing up. For T_{09} the timer is fixed to the table.
4. The subject actuates the hand to grasp the object. The object is then released by the operator. The subject then maintains the grasp for 3 seconds. For T_{09} the subject presses start and then waits 3 seconds.
5. Immediately following step 4 the subject rotates the hand slowly so that the palm is pointed downward and holds the grasp for three seconds. For T_{09} the subject should attempt to stop the timer within 3 seconds instead. This step is skipped for T_{18}.
6. The subject releases the object. Steps 3-6 are then repeated an additional two times for each object. Once completed three times, the next object is then presented to the subject and the procedure is repeated until every object has been grasped.

5.3 Scoring System

The scoring matrix in Table 5-3 shows the criteria for scoring each task of AHAP. Each task is scored based on the participant's ability to perform the grasp correctly and with exception to T_{09} and T_{18}, the participants' subsequent ability to maintain the grasp. A score of 1 in the grasping portion indicates that the grasp was executed as required, a score of 0.5 indicates that a grasp other than the grasp specified was performed, while a score of 0 indicates that the object could not be grasped. A score of 1 in the maintaining portion indicates that the prosthesis maintained the grasp with no movement of the object with reference to the hand, while a score of 0.5 indicates that some movement was observed without dropping the object. A score of 0 in the maintaining portion indicates the object was dropped. Scoring of T_{09} uses the grasping criteria twice for assessing the task, once for turning on the timer and once for turning the timer off. There is no maintaining score for T_{18}. The conditions for assessing whether the grasp was completed using the correct GT is presented in Table 5-4.

5.4 Outcome Measurements

Several useful measurements can be obtained by completing AHAP, namely: the overall GAS; the overall grasping scores and maintaining scores; the partial GASs; and the partial grasping scores and maintaining scores. These measurements are briefly discussed below. In general, partial scores measure the performance of the prosthesis for individual grasp types, whereas the overall score measures how well the prosthesis performed across all the tested grasp types.

5.4.1 Overall and Partial Grasp Ability Scores

The GAS is a broad measurement of hand function that includes both the grasping and the maintaining abilities of the tested prosthesis. The GAS is measured as a percentage of the total possible score achievable in AHAP. The GAS provides a convenient but general measurement of prosthetic hand function.

5.4.2 Overall and Partial Grasping and Maintaining Scores

The grasping and maintaining scores are a measure of how well the prosthesis performed in the grasping and maintaining portions of the AHAP measured as a percentage of the highest possible score of each respective portion. The grasping and maintaining scores can be described as the ability of the prosthesis to perform the correct grasp type specified for each task. Conversely, the maintaining score is a measure of the prosthesis' ability to maintain a stable grasp of an object in motion and after the gravitational benefit of having the prosthesis underneath the object is removed. These measurements are particularly useful for assessing and aiding in prosthesis design as they provide a more contextual view of the prosthesis' performance.

Table 5-3 AHAP scoring system adapted from Llop-Harillo et al. (2019)

Step	Task	Score	Criteria
4	Grasping - All	1	Grasp is completed with correct GT
		0.5	Grasp is completed but different GT to the one specified
		0	The hand cannot Grasp the object
5	Maintaining - All tasks except T_{09} and T_{18}	1	No visible motion of object w.r.t hand
		0.5	Object moves but is not dropped
		0	Object is dropped
	Grasping – T_{09}	1	Grasp is completed with correct GT
		0.5	Grasp is completed but different GT to the one specified
		0	Not completed within 3 seconds
	Task 18	NA	No points for this portion

Table 5-4 Requirement conditions for achieving correct grasp type adapted from Llop-Harillo et al. (2019)

Grasp Type	Conditions	
	Contact with object	Axial and planar
Hook (H)	Palmar side of 3 fingers	NA
Spherical grip (SG)	Palmar side of the thumb and all the phalanges of at least 3 fingers	NA
Tripod pinch (TP)	Radial side of the middle finger and palmar side of distal phalanges (DP) of thumb and index finger	NA
Extension grip (EG)	Palmar side of DP and intermediate phalanges (IP) of at least 3 fingers and palmar side of the thumb	The angle between axes of DP and object side in contact must be less than 30 degrees
Cylindrical grip (CG)	Palmar sides of the thumb and all phalanges of at least 3 fingers	The angle between the thumb axis and the axis of the object must be greater than 60 degrees
Diagonal volar grip (DVG)	Palmar side of thumb, palm and 3 fingers	The angle between the axis of the thumb and the symmetry plane of the object must be less than 30 degrees
Lateral pinch (LP)	Palmar side of the thumb and radial side of DP of the index finger	NA
Pulp pinch (PP)	Palmar side of thumb and DP of only one finger. The object must not touch the palm	NA
Index pointing (IP)	Palmar side or tip of DP of index finger and timer starts/stops	NA

6 Results and Discussion

This chapter presents the results and discussion of the design validation. Throughout the chapter, the various performance metrics achieved by the SATH are analysed including the GAS, the partial GAS, the grasping scores, and the maintaining scores. The performance of the SATH will be compared to that of the KIT Prosthetic Hand P2 (KIT2); a prosthesis that was assessed using SATH by Llop-Harillo et al. (2019). The full scoring table used for recording the individual score for each task is attached in Appendix C Table C-1.

6.1 Grasp Ability Score (GAS)

The SATH scored a GAS of 75% made up of a grasping score of 79% and a maintaining score of 69%. A comparison of these scores with that of the KIT2 can be seen in Figure 6.1.

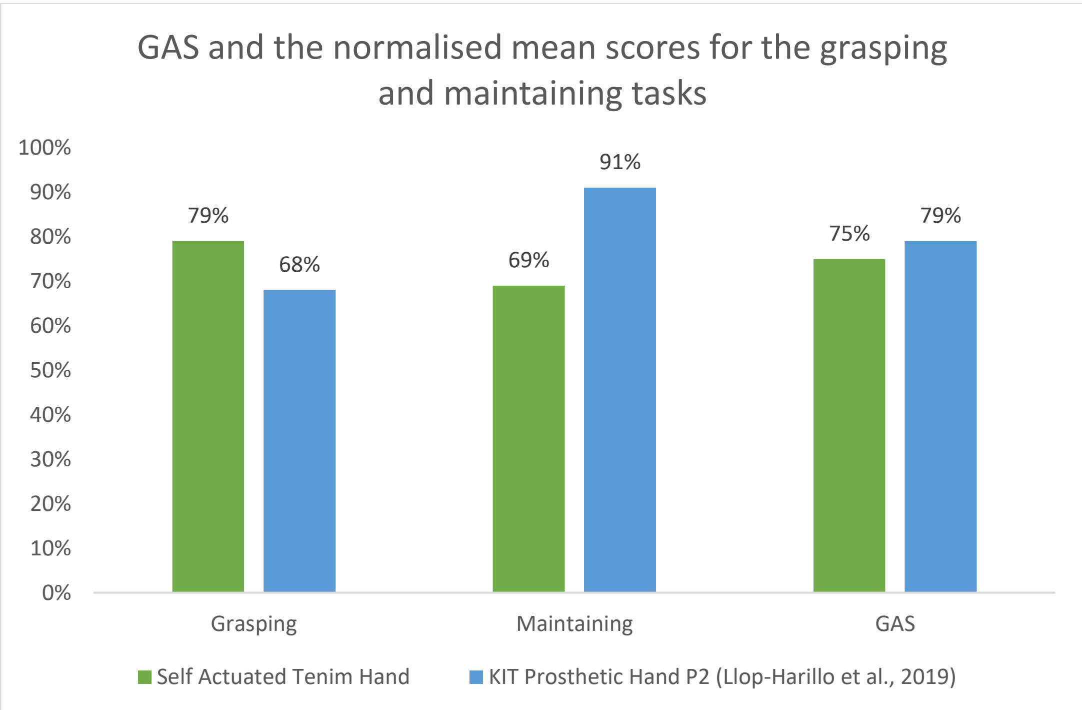


Figure 6.1 GAS and the normalised mean scores for the grasping and maintaining components of all the tasks for the Tenim Hand V2 and the KIT Prosthetic Hand P2

When comparing the grasping score of the two prostheses it was noted that, while both hands use similar under-actuated grasping mechanisms, the SATH had a superior grasping ability. This is perhaps explained by its adjustable thumb. The thumb was often adjusted in the one-minute practice session allocated before each task for better grasping outcomes. It was suspected that the lack of mobility in the KIT2's thumb may be a factor in its lower grasp score, especially in tasks that require adduction from the KIT2's abducted thumb position.

The lower maintaining score for the SATH may be explained by the use of compliant materials in the distal phalanges of the KIT2. Compliant materials would allow for better grip by causing greater friction and better positioning of the contact areas of the fingers. Although the SATH has silicon pads on the palmar surface of the distal phalanges, the compliance of the entire body of the KIT2's distal phalanges would allow for greater friction between the prosthesis and the object in a wider range of grasping scenarios. Llop-Harillo et al. (2019) showed that the addition of strategically placed friction pads could greatly increase the maintaining performance of an artificial hand in AHAP.

6.2 Partial Grasp Ability Scores

The partial GAS scores for the SATH are as follows: 100% for P; 100% for IP; 50% for PP; 83% for LP 50% for the DVG; 75% for CG, 64% for EG; 75% for TP; 97% for SG; and 89% for H. A comparison of the partial GAS scores for the SATH and KIT2 is shown in Figure 6.2. Although the KIT2 has a better overall GAS, the partial GAS shows that the two different prostheses are better at different GTs. The SATH performed better at the P, LP, SG and H grasps, whereas the KIT2 performed better at the PP, DVG, CG, EG and TP grasps. Analysing the performance of the SATH for the individual GTs will allow informed recommendations to be made for future work.

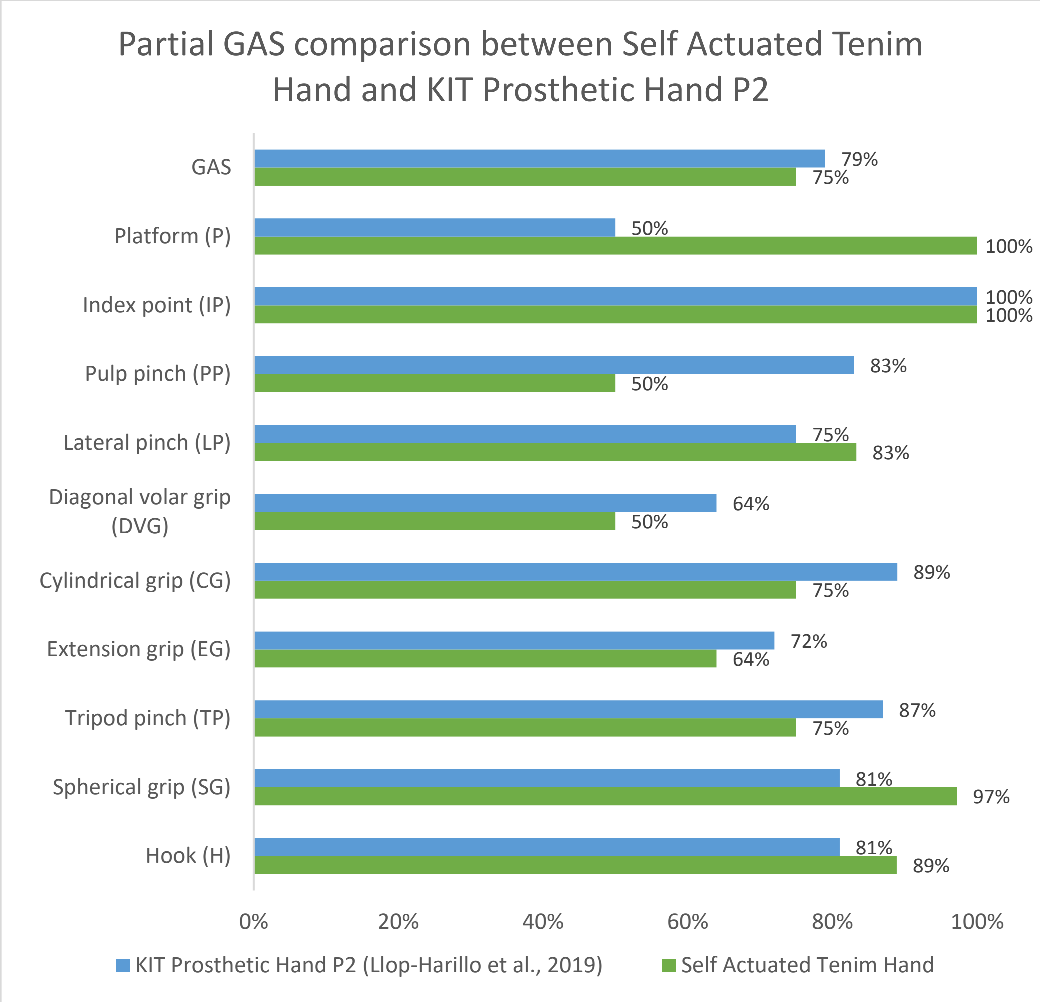


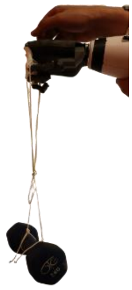
Figure 6.2 Partial GAS comparison between Tenim Hand V2 and KIT Prosthetic Hand P2

The remainder of this chapter is centred on discussing the performance of the SATH for the individual grasp types. *The 'Comments'* section in each table was used to record additional insight into the reason the SATH did not score 100% in a particular part of a task.

6.2.1 Hook

Table 6-1 shows the grasping and maintaining performance for the individual tasks requiring the H grasp while providing illustrated evidence of each completed task. The SATH achieved perfect performance in the grasping portions of the tasks with the SATH scoring 100% for T_{01}, T_{09} and T_{19}. The maintaining performance, however, showed mixed results with the respective scores for T_{01}, T_{09} and T_{19} being 83%, 100% and 50%.

Table 6-1 Results for the hook tasks of the AHAP for the Tenim Hand V2 showing evidence for each completed task with its respective maintaining and grasping scores. Also presented is the partial GAS for the Tenim Hand V2 and KIT Prosthetic Hand P2. "G" and "M" respectively represent the grasping and maintain performance for the individual tasks.

	T_{01} – skillet lid	**T_{09} – pitcher base**	**T_{19} – rope with weight**
Task			
Comment	Object moved but not dropped in one maintaining part of the test	None	Object moved but not dropped in all maintaining part of the test
G	100%	100%	100%
M	83%	100%	50%
GAS	$GAS_H = 89\%$ KIT P2 $GAS_H = 81\%$		

In one of the tasks for T_{01}, the skillet moved as the hand was being turned over, while in all tasks for T_{19} the rope moved under the same circumstances; however, the objects were never dropped for any of the H tasks. The grasping surface area in T_{09} is greater than that of T_{01} and T_{19}. The difference in this grasping surface of the different objects is likely the cause for the differences in maintaining performance. This is supported by the SATH scoring maintaining scores in the tasks in descending order from objects with the greatest to least grasping surface are. A possible remedy to this phenomenon would be the addition of friction pads to the palmar side of the phalangeal joints. In theory, this should lower the grasping surface are required to maintain a stable grasp on a given object.

6.2.2 Spherical Grip

Table 6-2 shows the grasping and maintaining performance for the individual tasks requiring the SG grasp while providing illustrated evidence of each completed task. The SATH showed perfect performance for the grasping portions of the tasks. The maintaining performance was almost as promising, scoring 100% in maintaining parts T_{11} and T_{20} while scoring 83% in T_{02}.

Table 6-2 Results for the spherical grip tasks of the AHAP for the Tenim Hand V2 showing evidence for each completed task with its respective maintaining and grasping scores. Also presented is the partial GAS for the Tenim Hand V2 and KIT Prosthetic Hand P2. "G" and "M" respectively represent the grasping and maintain performance for the individual tasks.

	T02 – apple	**T11 - softball**	**T20 – mini soccer ball**
Task			
Comment	Object moved but not dropped in one maintaining part of the task	None	None
G	100%	100%	100%
M	83%	100%	100%
GAS	$GAS_{SG} = 97\%$ KIT P2 $GAS_{SG} = 81\%$		

The SATH forfeited a perfect performance for T_{02} due to movement of the apple as the prosthesis was being turned over in one round of T_{02}. The movement of the apple is perhaps attributed to its relatively low friction surface. Friction pads on both the palmar phalangeal surfaces and the palmar surface itself could aid in improving the maintaining performance of the SATH for SG tasks.

6.2.3 Tripod Pinch

Table 6-3 shows the grasping and maintaining performance for the individual tasks requiring the TP grasp while providing illustrated evidence of each completed task. The SATH scored 100% for T_{12}, T_{21} and 83% for T_{03} in the grasping portions of the tasks.

In one round of the T_{03} task, the pen slipped into an incorrect GT as the hand was grasping the marker. Although at 83% a relatively high grasping score was achieved for T_{03}, the rigid nature of the T2s fingers prevented the SATH from scoring higher. The rigidity of the fingers made positioning the marker in between the index and middle digits of the SATH, as required in Table 5-4, difficult. A possible solution to this would be to use phalanges made from compliant materials such as those used in the KIT2.

Table 6-3 Results for the tripod pinch tasks of the AHAP for the Tenim Hand V2 showing evidence for each completed task with its respective maintaining and grasping scores. Also presented is the partial GAS for the Tenim Hand V2 and KIT Prosthetic Hand P2. "G" and "M" respectively represent the grasping and maintain performance for the individual tasks.

Task	**T_{03} – large marker** 	**T_{12} – tuna can** 	**T_{21} – golf ball** 
Comment	Object incorrectly grasped one grasping part of the task	Object was dropped in all maintaining parts of the task	Object was dropped in one maintaining part of the task
G	83%	100%	100%
M	100%	0%	67%
GAS	$GAS_{TP} = 75\%$ KIT P2 $GAS_{TP} = 87\%$		

For the maintaining portion of the tasks, the SATH scored 100%, 0% and 67% for tasks T_{03}, T_{12} and T_{21} respectively. The relatively low friction of the tuna can surface resulted in the can being dropped every time the SATH was turned over. The golf ball was only dropped once and could be explained by simply not grasping the object with enough force. Once more, it is postulated that high-friction pads on the contact surfaces of the SATH would aid in improving the maintaining score.

6.2.4 Extension Grip

Table 6-4 shows the grasping and maintaining performance for the individual tasks requiring the EG grasp while providing illustrated evidence of each completed task. The SATH showed good performance for the grasping portions of the tasks, scoring 100% for each task. The maintain scores, however, were less promising with the SATH scoring 0%, 33% and 100% for tasks T_{04}, T_{13} and T_{22} respectively.

The weight of the relatively heavy plate and cracker box required more surface contact from the SATH to adequately complete the maintaining portion of the tasks. As shown in the photographs of the SATH holding the plate and the pudding box in Table 6-4, the thumb would only make contact with the object through the distal tip of the distal phalange. There was thus very little contact area opposing the support provided by the phalanges of the 2nd to 5th digits. Addressing this issue will require further investigation into the dynamic and static properties of the thumb.

Table 6-4 Results for the extension grip tasks of the AHAP for the Tenim Hand V2 showing evidence for each completed task with its respective maintaining and grasping scores. Also presented is the partial GAS for the Tenim Hand V2 and KIT Prosthetic Hand P2. "G" and "M" respectively represent the grasping and maintain performance for the individual tasks.

	T_{04} - plate	**T_{13} – cracker box**	**T_{22} – pudding box**
Task			
Comment	Object was dropped in all maintaining parts of the task	Object grasped but incorrectly. Object was dropped in one maintaining part of the task and moved but not dropped in the other two	None
G	100%	50%	100%
M	0%	33%	100%
GAS	GAS_{EG} = 64% KIT P2 GAS_{EG} = 72%		

6.2.5 Cylindrical Grip

Table 6-5 shows the grasping and maintaining performance for the individual tasks requiring the CG grasp while providing illustrated evidence of each completed task. The SATH achieved perfect scores for the grasping portion of T_{05}, T_{14} and T_{23} as well as the maintaining portion of T_{05} and T_{23}. In contrast, a score of 0% was achieved for the maintaining portion of T_{14}.

Table 6-5 Results for the cylindrical grip tasks of the AHAP for the Tenim Hand V2 showing evidence for each completed task with its respective maintaining and grasping scores. Also presented is the partial GAS for the Tenim Hand V2 and KIT Prosthetic Hand P2. "G" and "M" respectively represent the grasping and maintain performance for the individual tasks.

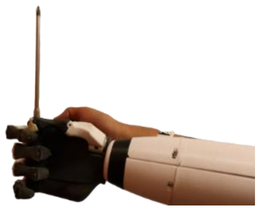
Task	**T_{05} – chips can** 	**T_{14} – coffee can** 	**T_{22} – power drill** 
Comment	None	Object dropped in all maintaining parts of the task	None
G	100%	50%	100%
M	100%	0%	100%
GAS	GAS_{CG} = 75% KIT P2 GAS_{CG} = 89%		

The lack of maintaining ability could be explained by the size of the coffee can when compared to the other objects in this task group. In the design, process efforts were made to increase the maximum size of objects that could be grasped. Despite this being partially achieved, evidenced by the SATH scoring 50% for the grasping portion of T_{14}, it has become apparent through this validation process that fitting within the grasp of the SATH does not necessarily signify that the grasp can be maintained. It was noted that unlike with the drill and chips can, the coffee can made no contact with the palmar surface of the prosthesis and thus had its whole weight supported by the phalanges of the thumb and fingers. The positioning and geometry of the thumb prevent contact from being made between the palmar surface and large diameter objects. Further enquiries are required to rectify this occurrence.

6.2.6 Diagonal Volar Grip

Table 6-6 shows the grasping and maintaining performance for the individual tasks requiring the DVG grasp while providing illustrated evidence of each completed task. In both the T_{06} and the T_{15} task the SATH achieved scores of 50% and 100% for grasping and maintaining respectively.

Table 6-6 Results for the diagonal volar grip tasks of the AHAP for the Tenim Hand V2 showing evidence for each completed task with its respective maintaining and grasping scores. Also presented is the partial GAS for the Tenim Hand V2 and KIT Prosthetic Hand P2. "G" and "M" respectively represent the grasping and maintain performance for the individual tasks.

Task	**T_{06} –screwdriver** 	**T_{15} – spatula** 	**T_{24} – skillet** 
Comment	Object grasped incorrectly for all grasping parts of the task	Object grasped incorrectly for all grasping parts of the task	Object could not be grasped at all
G	50%	50%	0%
M	100%	100%	0%
GAS	GAS_{DVG} = 50% KIT P2 GAS_{DVG} = 64%		

The relatively low scores for the grasping portions of tasks T_{06} and T_{15} was a result of the thumb axis not being parallel to the axis of symmetry of the object, as required in Table 5-4. The DVG approximated to be equivalent to the light tool grasp from Table 2-5 is ranked near the bottom of the ranked grasps required from a prosthesis. Additional investigations are required to determine whether the current manner through which the SATH performs the DVG is sufficient for performing ADLs.

The SATH was not capable of grasping the skillet handle using the DVG or otherwise. The low friction surface of the metal handle combined with the weight of the skillet resulted in the skillet immediately slipping from the grasp of the SATH. The addition of friction pads would aid the SATH in grasping the skillet handle more effectively, however, the SATH would still not achieve the correct GT as the prosthesis' geometry make it incapable of achieving the DVG grasp.

6.2.7 Lateral Pinch

Table 6-7 shows the grasping and maintaining performance for the individual tasks requiring the LP grasp while providing illustrated evidence of each completed task. In the T_{25} task, the SATH achieved 100% for both grasping and maintaining portions of the task. The SATH achieved 100% and 50% for the grasping and maintaining portions of the T_{07} task respectively. The SATH achieved 50% and 100% for the grasping and maintaining portions of the T_{16} task respectively.

The relatively low score for the maintaining portion of the T_{07} can perhaps be explained by the smooth surface of the bowl. While the bowl was never dropped, the bowl slipped every time the hand was rotated. The addition of friction pads on the radial side of the phalanges may serve to address this issue.

The low score for the grasping portion of the T_{16} task can be explained by the interaction of the two hard plastics of the clamp and the phalanges. The clamp, as sufficient grasping force was being applied, rotated from the correct position, as shown in Table 5-2, to the incorrect position shown in

Table 6-7. The hard plastics would simply side across each other as sufficient force to maintain the grasp was being applied. The unwanted rotation may be negated by incorporating more compliant materials into the phalanges of the SATH.

Table 6-7 Results for the lateral pinch tasks of the AHAP for the Tenim Hand V2 showing evidence for each completed task with its respective maintaining and grasping scores. Also presented is the partial GAS for the Tenim

Hand V2 and KIT Prosthetic Hand P2. "G" and "M" respectively represent the grasping and maintain performance for the individual tasks.

Task	**T_{07} - bowl** 	**T_{16} – XS clamp** 	**T_{25} – key** 
Comment on Task	Object moved but not dropped in all maintaining parts of the test	Object grasped but incorrectly for all grasping parts of the test	None
G	100%	50%	100%
M	50%	100%	100%
GAS	GAS_{LP} = 83% KIT P2 GAS_{LP} = 75%		

6.2.8 Pulp Pinch

Table 6-8 shows the grasping and maintaining performance for the individual tasks requiring the PP grasp while providing illustrated evidence of each completed task. The SATH achieved perfect scores for the T_{17} task. The SATH however, failed to complete a score in the T_{25} task, scoring 0% for both the grasping and maintaining portions of the task. 33% and 67% were scored for the grasping and maintaining portions of the T_{08} task respectively.

Table 6-8 Results for the pulp pinch tasks of the AHAP for the Tenim Hand V2 showing evidence for each completed task with its respective maintaining and grasping scores. Also presented is the partial GAS for the Tenim Hand V2 and KIT Prosthetic Hand P2. "G" and "M" respectively represent the grasping and maintain performance for the individual tasks.

	T_{08} – small marker	**T_{17} - pear**	**T_{25} – 10mm washer**
Task			No picture was taken.
Comment on Task	Object grasped incorrectly for two grasping parts of the task and not grasped at all for one grasping part of the task. When the object was grasped the grasp was maintained	None	Object could not be grasped at all
G	33%	100%	0%
M	67%	100%	0%
GAS	GAS_{PP} = 50% KIT P2 GAS_{PP} = 83%		

The current geometric constraints of the SATH do not allow the thumb to directly oppose any of the other phalanges. On larger objects such as the pear, this does not necessarily pose a problem, as seen with the high scores for T_{17}. However, on smaller slippery objects such as the marker and the washer, these geometric constraints prevent the SATH from completing these grasps. Solving this issue may involve investigating the incorporation of a mechanism for adjusting one or more of the phalanges in a manner that causes at least one of the phalanges to directly oppose the thumb under flexion.

6.2.9 Non-Grasping Postures: Index Pointing & Platform

Table 6-9 shows the grasping and maintaining performance for the individual tasks requiring the non-grasping postures while providing illustrated evidence of each completed task. The SATH scored 100% for both the grasping and maintaining portions of the T_{09} task and scored 100% for the T_{18} task.

Table 6-9 Results for the index pointing and platform tasks of the AHAP for the Tenim Hand V2 showing evidence for each completed task with its respective maintaining and grasping scores. Also presented is the partial GAS for the Tenim Hand V2 and KIT Prosthetic Hand P2. "G" and "M" respectively represent the grasping and maintain performance for the individual tasks.

Task	**T_{09} – Timer** 	**T_{18} – Plate** 
Comment	None	None
G	100%	100%
M	100%	NA
GAS	GAS_{IP} =100% KIT P2 GAS_{IP} = 100%	GAS_{P} = 100% KIT P2 GAS_{P} = 50%

7 Conclusions and Recommendations

This study aimed to develop a prosthesis that can bridge the gaps between cost and functionality of body-driven and myoelectric prostheses through the development of a prosthesis that satisfies the grasping and functional requirements found in the literature of prosthesis users.

Achieving this aim was subject to meeting the following objectives:

- Identifying the needs of upper limb amputees from the literature including reasons for prosthesis abandonment, the grasps required in a functional prosthesis and other concerns relevant to prosthesis users.
- The design of a functional prosthesis through:
  - The design of a prosthesis that addresses the concerns and requirements discovered from the literature and clinician consultation and can perform the identified essential grasps.
  - The design of an actuator system that is integrated into the mechanical design of the prosthesis.
- Performing design validation of the prosthetic with its integrated actuator system through an independently developed protocol for assessing hand function

7.1 Conclusions

7.1.1 Upper Limb Amputee Needs

From the literature, it was found that many users of body-driven prostheses in LMICs abandon their devices due to the lack of comfort and input forces these devices require. As a result of abandoning their prostheses, they suffer overuse injuries in their sound limb. The users of such devices often cannot afford myoelectric devices however are willing to pay more than what they pay for body-driven prostheses provided the prostheses they pay for provide more function. By focusing on the most important grasps required in ADLs, shown in Table 7-1, effective and functional prostheses can be developed. Furthermore, additions such as adjustable wrists were shown to greatly increase the function of hand prostheses.

Table 7-1 Ranked list of grasp types for prosthesis design. The number in brackets indicates the grasp's GRASP Taxonomy designation.

Ranked list of Grasp Types

1. Medium Wrap (3)	8. Power Sphere (11)
2. Precision disk (12)	9. Power Disk (10)
3. Lateral pinch (16)	10. Prismatic 2 Finger (8)
4. Tripod (14)	11. Prismatic 3 Finger (7)
5. Lateral Tripod (25)	12. Light Tool (5)
6. Writing Tripod (20)	13. Tip Pinch (24)
7. Index Finger Extension (17)	

7.1.2 Prosthesis Design

The Tenim Hand, a body driven prosthesis capable of many different grasps, was used as a basis for the development of a prosthetic system that would meet the aim of this study. The hand was modified to overcome issues that were identified upon replication of the original prototype. Through the addition of systems such as the wrist adjustment mechanism and the actuator system, the Self Actuated Tenim Hand (SATH) was developed. The wrist mechanism allows the SATH to be operated in different configurations of pronation and supination. The SATH incorporates an electromechanical actuator that can provide 280N of force to the modified Tenim Hand. To activate the actuator the user simply presses a trigger underneath their able limb with said limb, thus greatly reducing the activation forces required when compared to body-driven prostheses. Many myoelectric devices use multiple actuators to achieve activation. Using the single actuator, the simple trigger mechanism and the under-actuation feature that characterized the Tenim Hand, the SATH should be significantly cheaper than its myoelectric counterparts.

7.1.3 Design Validation

The experimental validation of the SATH, through AHAP, can be considered successful having achieved a GAS 75% and grasping and maintaining scores of 79% and 69% respectively. For comparison, the more advanced KIT2 scored a GAS of 79% and 68% and 91% for grasping and maintaining respectively. The KIT2 scored higher than the SATH in the maintaining portion of the GAS. While the SATH outscored the KIT2 in the grasping portion, possibly explained by the SATH's adjustable thumb and wrist, resulting in little difference between the overall GAS of the two.

The SATH scored above 50% for every partial GAS and above 75% for five of the eight grasp types and both non-grasping tasks. The SATH only noticeably struggled with two grasps, namely the DVG and PP grasps (the equivalent of light tool and tip pinch the two lowest-ranked grasps in Table 7-1). The SATH was geometrically constrained from achieving these grasps and further investigation is required to address these issues.

The other notable struggle the SATH had included objects slipping in the maintaining portions of the tasks. In tasks where slipping was an issue the SATH generally managed to not drop the object. Solutions such as the addition of gripping pads and to the contact surfaces of the SATH and the utility of compliant joints are to be investigated to alleviate these shortcomings.

7.1.4 Overall Outcomes

Through a focus on addressing the needs of amputees, the SATH was successfully designed to increase prosthetic hand function when compared to the body-driven alternatives. The SATH was able to perform each of the grasping and non-grasping required in AHAP to at least 50% of the level of healthy limb function and scored a total GAS comparable with the more complex KIT2 prosthesis. On balance, the SATH's performance in the AHAP can be considered successful with the device only requiring minor updates to increase its already satisfactory performance. Once the issues found through the design validation process are addressed, the SATH can be validated for use by amputees.

7.2 Recommendations and Future Works

7.2.1 Design Recommendations

The SATH on balances can be considered a successful proof of concept however some deficiencies were noted in the design validation. These deficiencies include shortcomings in the DVG and PP grasps and the objects slipping as the hand was being moved. The following design recommendations are intended to nullify these deficiencies:

- Investigate the addition of a mechanism for rotating the pose of one or more of the proximal phalanges so that the finger may be pointed directly toward the thumb would allow the distal phalanges of the thumb and said finger to be in direct opposition. This should increase the performance of the SATH in the pulp pinch tasks.
- Investigate the addition of high-friction gripping pads to the contact surfaces of the SATH. This should improve the performance of the SATH in maintaining grasps.
- Investigate the addition of compliant joints to the SATH. This should improve the performance of the SATH in maintain grasp by allowing deviations in the positions of the phalanges that may allow them to better wrap around an object.

7.2.2 Future Testing

The design validation of the SATH was intended to verify the SATH as a proof of concept. Once the design recommendations have been investigated and implemented, the following recommendations are intended to assist in validating the device for use by amputees:

- Perform usability assessments of the SATH using amputee subjects.
- Revalidate the updated SATH using AHAP and the YCB Object Set using amputee subjects.
- Perform the above two validation exercises on the original Tenim Hand and other commercially available prosthetic devices to set realistic baselines for the SATH.

- Perform a costing analysis on the SATH when using commercially viable production techniques such as injection moulding instead of 3D printing to measure the cost-effectiveness of the device when compared to commercially available prostheses.

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Appendix A Functional Review of The Tenim Hand

Various experiments were conducted to validate the design of the Tenim Hand. These experiments and their results are briefly discussed below.

A.1 Grasping Capabilities of the Hand Prosthesis

This experiment aimed to assess whether the prosthesis can achieve various precision and power grasps. Based on the work of Zheng, et al. (2011) and the grasps used in SHAP (Light et al., 2002), Tenim identified seven essential grasps for the validation of the Tenim Hand. The seven grasps are listed in Table A-1 along with the corresponding grasp in the GRASP taxonomy and evidence for achieving the grasp.

The experiment concluded that the prosthesis can perform power grips with relative ease, however, the precision grips took multiple efforts to achieve these grasps. Tenim states that a possible reason for these difficulties is the shape and trajectory of the thumb. The author has conducted similar tests on a reproduced Tenim Hand and has found these results mostly consistent. However, issues with the trajectory of the other fingers were also noted as a contributor to the difficulties in achieving power grips. The author also notes that the small size of the angle of flexion of the metacarpophalangeal joint of the thumb greatly limits the size of the object that can be grasped by the Tenim Hand.

A.2 User and Prosthetist Feedback

As part of the design validation of the Tenim Hand, a small study was conducted in which patient and prosthetist feedback was collected (Tenim, 2014). Two patients and one prosthetist were involved in the study. The prosthetist acted as a bridge between Tenim and the patients by both fitting the prosthesis and tending to the individual needs of the patients. Feedback was collected in the form of a prosthesis hand evaluation questionnaire (PHEQ). The feedback gathered from the patients and prosthetist are presented below in Table A-2 and

Table A-3 Prosthetist Feedback adapted from Tenim (2014)

respectively. Although all the findings from Tenim's study are presented, this study is primarily focused on finding and recommendations that would contribute to the function of the prosthesis.

As evidenced by Table A-2 and Table A-3, feedback from the prosthesis users were mixed. One user withdrew from the study due to aesthetic purposes, while another left-hand amputee using a right-hand prosthesis had generally positive feedback. Their negative feedback was focused on the inability of the Tenim Hand to perform precision grasps. The prosthetist recommendation, shown in Table A-3, to adjust the closing trajectory of the first three digits for better repeatability in pinch grasps mirrors the sentiment of the amputee. While the inability to perform certain grasps was the most significant functional deficiency of the Tenim Hand, other recommendations and deficiencies were considered in the design chapters.

Table A-1 Table showing the achieved grasps of the Tenim Hand adapted from Tenim (2014)

Grasp Classification		Corresponding grasp in GRASP taxonomy	Evidence of achieved grasp
Power	Medium Wrap	3	
	Power Sphere	11	
	Lateral Pinch	16	
Precision	Index Finger Extension	17	
	Tripod Grasp	14	
	Thumb – 3 Finger (tip grasp)	7	
	Precision Sphere	13	

Table A-2 Patient feedback adapted from Tenim (2014)

	Positive Feedback	**Negative Feedback**
Patient 1		Raised concerns regarding the colour of the prosthesis and immediately withdrew from participation
Patient 2 (left-handed patient fitted with right-handed prosthesis)	Easily able to grasp uniform and non-uniform objects in various power grasps	Unable to perform precision grasps
	Enjoyed low effort required to actuate prosthesis	
	Would be willing to use the device for a longer period if the device was right-handed	

Table A-3 Prosthetist Feedback adapted from Tenim (2014)

	Positive Feedback	**Recommended Alterations**
Aesthetic	The proportions, lines and shape of the palmar structure are acceptable and look good.	Shorten the length of the proximal digits. Although they are anthropometric, patients psychologically perceive the non-natural hand to be larger than it is.
	The central exit location of the actuating cable through the wrist stem of the prosthesis (which usually exits dorsally in other prostheses), allows the cable to travel through the patient's socket, instead of on top of it, exiting higher up the arm. This allows the user to hide the cable and give a better look at the hand.	Adjust the initial rest position of the digits to mimic the resting position of the natural hand.
	The customisation to each patient such as size, proportion, embossing and engraving through additive manufacturing is beneficial.	Add a convex surface onto the dorsal surface of the proximal phalanges for "flow".
		Investigate different colours for the hand, or perhaps a glove.
Functional	The hand is lightweight and requires very low actuation force compared to other hands.	The closing trajectory of the first three digits should be adjusted to allow repeatable pinch grasps.
	The release button of the ratchet mechanism provides good resistance and is easy to engage and disengage.	A PTFE or low-friction lining should be inserted into a hole in the wrist stem, where the primary input cable enters the prosthesis to prevent wear.
	The conformability of the hand's digits to regular and irregularly shaped objects is very good.	Reduce the rotation positions of the thumb swivel to three instead of five. Namely, lateral grasp, index-finger pinch, and tripod grasp. This was suggested to reduce the choices a patient has and thus the cognitive effort.
	The stem easily fits onto standard wrist units and requires only a single attachment for the hand and the actuating cable in the distal portion of the patient's socket, due to their coinciding central location.	Alter the shape of the thumb's distal phalanx to be more convex to allow normal contact interaction with the grasped objects at various points throughout the closing trajectory.
		As expected, the prosthesis does not provide sufficient extensive force to extend the hand and the shoulder harness due to the harnesses own inherent internal friction. An external spring mechanism to overcome harness friction should be included by the prosthetist (i.e. a self-sufficient harness should be made or designed).
		Future myoelectric versions could use a low-cost linear potentiometer in tandem with a harness, instead of costly surface electrodes to trigger a motor's flex-extend command.

Appendix B Acquired Component Specifications

Table B-1 Lead screw and nut specifications

Specification	Value
Major Diameter [mm]	8
Pitch [mm]	2
Load, F [N]	280
Friction coefficient, µ	0.2
Thread angle, 2α	30
Lead, l	8
mean diameter, d_m	7.25

Table B-2 DAGU Wild Thumper Motor 75:1 specification

Specification	Value
Motor Torque, T_m [kg.cm]	7.4
Motor Torque, T_m [N.mm]	726
Stall Current, I_{max} [A]	3.4
Dimensions, $diameter \times length$ [mm]	25x69.5
Voltage, V_m [V]	6.0-7.5
Gear Ratio, GR_m	75:1

Table B-3 Specifications of the Arduino Nano

Specification	Value
Input voltage [V]	7-12
Operating voltage/logic level [V]	5
Digital input/output pins	22 (6 PWM)
PWM Frequency	490Hz
Analogue input	8
Size [mm x mm]	18x45
Current Draw [mA]	19-200

Table B-4 Specifications of the Monster Moto Arduino shield

Specification	**Value**
Input voltage [V]	5.5-16
Max. current output (instantaneous)	30A
Max. current output (continuous)	14A
Max. PWM Frequency	20kHz
Driver current draw (excludes output current drawn by motor)	0.012-20mA

Table B-5 Specifications of the Ansmann 7.4V Li-ion battery

Specification	**Value**
Nominal voltage [V]	7.4
Max. Voltage [V]	8.6
Nominal Capacity [mAh]	2600
Min. Capacity [mAh]	2500
Max. Discharge current [mA]	5000

Appendix C AHAP Results for the SATH

Table C-1 Scoring of SATH in AHAP design validation Experiment

GT	Task No.	Object	S1 grasp	S1 maintain	S2 grasp	S2 maintain	S3 grasp	S3 maintain	Task Total	GT Total	GT Total Norm	Grasp	Maintain
Hook (H)	1	Skillet Lid	1	0.5	1	1	1	1	5.5			100	83.33
	10	Pitcher base	1	1	1	1	1	1	6			100	100
	19	Wood blocks with rope	1	0.5	1	0.5	1	0.5	4.5	16	88.89	100	50
Spherical grip (SG)	2	Plastic apple	1	1	1	0.5	1	1	5.5			100	83.33
	11	Softball	1	1	1	1	1	1	6			100	100
	20	Mini soccer ball	1	1	1	1	1	1	6	17.5	97.2	100	100

Table C-2 (cont.) Scoring of SATH in AHAP design validation Experiment

Tripod pinch (TP)	3	Large marker	1	1	0.5	1	1	1	5.5			83.33	100
	12	Tuna can	1	0	1	0	1	0	3			100	0
	21	Golf ball	1	0	1	1	1	1	5	13.5	75	100	66.67
Extension grip (EG)	4	Plate	1	0	1	0	1	0	3			100	0
	13	Cracker box	0.5	0	0.5	0.5	0.5	0.5	2.5			50	33.33
	22	Chocolate pudding	1	1	1	1	1	1	6	11.5	63,88889	100	100
Cylindrical grip (CG)	5	Chips can	1	1	1	1	1	1	6			100	100
	14	Coffee can	0.5	0	0.5	0	0.5	0	1.5			50	0
	23	Power drill	1	1	1	1	1	1	6	13.5	75	100	100

Table C-3 (cont.) Scoring of SATH in AHAP design validation Experiment

Diagonal volar grip (DVG)	6	Screw driver	0.5	1	0.5	1	0.5	1	4.5			50	100
	15	Spatula	0.5	1	0.5	1	0.5	1	4.5			50	100
	24	Skillet	0	0	0	0	0	0	0	9	50	0	0
Lateral pinch (LP)	7	Bowl	1	0.5	1	0.5	1	0.5	4.5			100	50
	16	Small clamp	0.5	1	0.5	1	0.5	1	4.5			50	100
	25	Key	1	1	1	1	1	1	6	15	83.33	100	100
Pulp pinch (PP)	8	Small marker	0	0	0.5	1	0.5	1	3			33.33	66.67
	17	Plastic pear	1	1	1	1	1	1	6			100	100
	2	10mm washer	0	0	0	0	0	0	0	9	50	0	0

Table C-4 (cont.) Scoring of SATH in AHAP design validation Experiment

Index point (IP)	26	Timer	1	1	1	1	1	1	6	6	100	100	100
Platform (P)	18	Plate	1		1		1			3	100	100	0
										114	74.51	79.49	69.33