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Design of an Upper Limb 3D Printed Prosthesis for Developing Countries

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ABSTRACT

The current solutions for upper limb prosthetics are expensive and provide limited functions. This project aimed to create an equal opportunity for people living in developing countries to make use of a high-quality functional prosthetic that would satisfy their needs. This was achieved through 3D printing. This project undertook an in-depth investigation into the desires of amputees and the anthropometrics behind the workings of a human hand by means of a literature review. From this, three concepts were conceived for a prosthesis and eventually combined to create an enhanced detailed CAD model in CATIA V.5. This model was optimised to reduce mass using topology optimisation in Hyper works. The final model resulted in an affordable prosthetic (roughly £316.43), which was lightweight (248g) and functional. The functionality was proven with a 3D printed prototype which could be controlled with wires to perform typical activities of daily living.

Introduction

Upper limb prostheses are required for people who have lost or partially lost their arm. The human hand is an integral part of human life and interacting with the environment around us. It is a key element of biology that sets us apart from other mammals, particularly due to our opposable thumbs. This makes the loss of an upper limb devastating to a person. The rise of new technologies, the implication of a missing limb can be reduced by replicating what was lost. These new technologies are expensive and quality prosthetics are only available to those who can afford them. In the developing world, these expensive prosthetics are rarely a viable option. The rise of what is known as the fourth industrial revolution (Industry 4.0) introduces brand new technologies which advance the way industry can manufacture quicker, more affordably and digitally. Additive manufacturing (3D printing) can cut costs and introduce active prosthetics to a wider audience. In developing countries many amputees are farmers, nomads, herdsmen and refugees; they rely on the use of two working arms for physical labour to survive. Not only does the loss of an upper limb have impact on the physical capabilities of a person but it also has a negative impact on their social lives. The aim was to design an upper limb prosthetic which is more affordable to those living in the developing world than current products on the market. It had to be adjustable, comfortable and facilitate activities of daily living (ADLs) [1]. The following are the objectives required to achieve this goal:

1. Investigate the requirements of a prothesis for upper limb amputees, what the key functions of a prosthetic arm are and the capabilities of 3D printing.
2. Define the requirements for the prosthesis which satisfy consumer needs.
3. Design three concepts which satisfy the above.

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4. Choose a final prototype ready definition.
5. Manufacture a prototype which can be tested.

For this project, one of the hardware driven technologies includes 3D printing. 3D printing involves the creation of 3D objects by joining and solidifying a variety of materials. This technology supports the rapid prototyping in product development and enables customised production and local or near-shore manufacturing [2]. In terms of this project, this would reduce manufacturing costs for the consumer as the prosthetic could be manufactured locally. Finite Element Analysis (FEA) is intensively and increasingly used in the product development process. It provides major improvements in productivity when creating CAD models. Hence, the design of the prosthesis in this project will be created in CATIA V.5. Typically, topology optimisation results in complex shapes which are difficult to manufacture. With industry 4.0, 3D printing allows for the manufacture of these complex shapes [3].

The Human Hand

For a greater understanding of the requirements for a prosthesis, anatomical knowledge of the human hand is crucial. The human arm is used for physical and social interactions. We also use the human hand for exploring our environments. It can move in 27 degrees of freedom (DOFs) (Figure 1) [4]. The hand consists of 5 digits, the 4 fingers can move in 4 DOFs each, 3 DOFs for extension and 1 for abduction. The thumb requires a greater range of movement, thus has 5 degrees of freedom. This includes abduction, extension (like fingers) and then opposition and retro position. These last 2 DOF allow the thumb to reach across the palm of the hand. This allows each finger to contact the thumb. Finally, there are 6 degrees of freedom in the wrist (Figure 2) [5,6]. The loss of an upper limb is categorised into different levels depending on the extent of the amputation; transhumeral, transradial, wrist disarticulation, transcarpal, shoulder disarticulation, elbow disarticulation, and forequarter [7] (Figure 3). These will be referred to throughout the article [8].

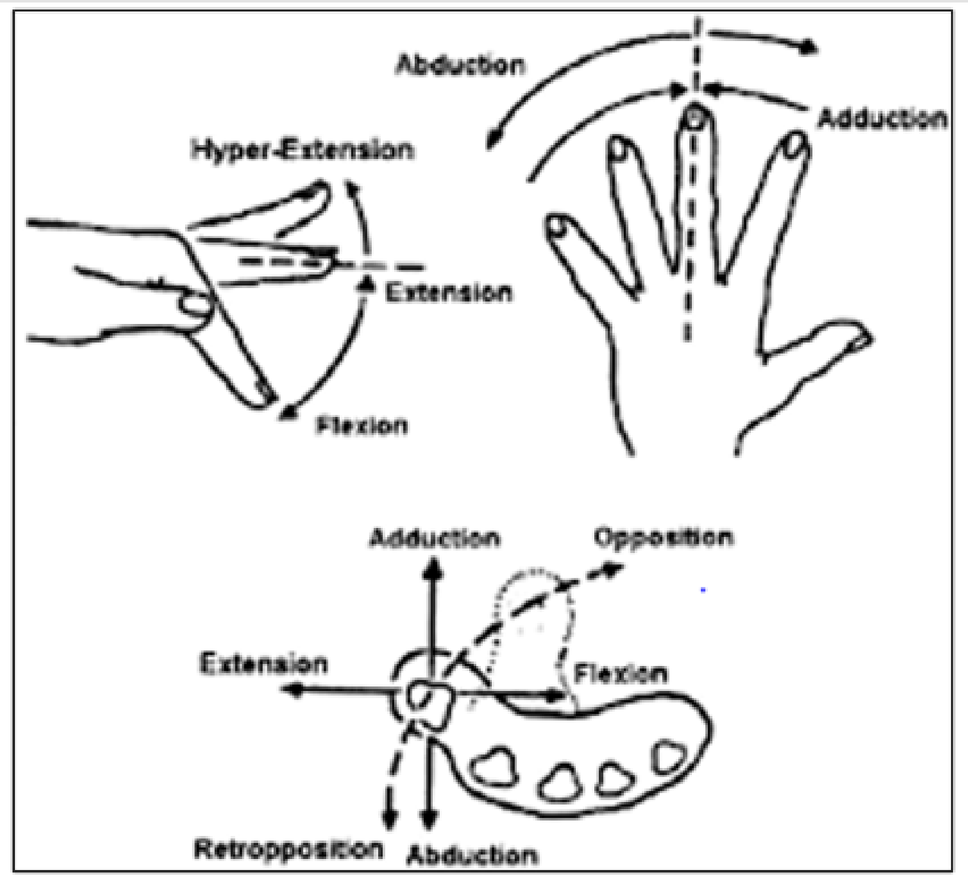

Figure 1: Degrees of Freedom for digits [5].

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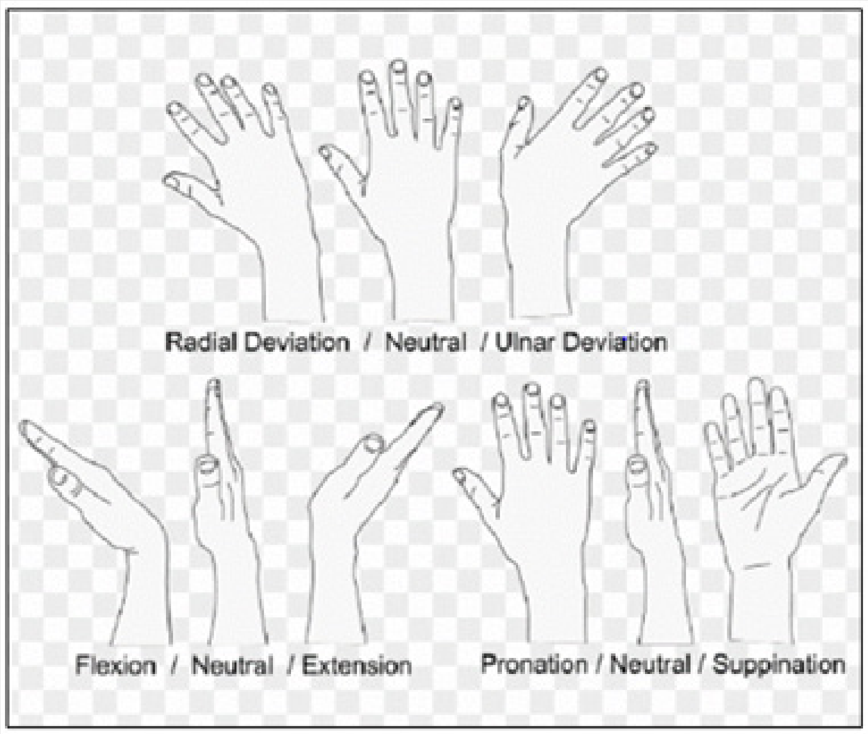

Figure 2: Degrees of Freedom for wrist [6].

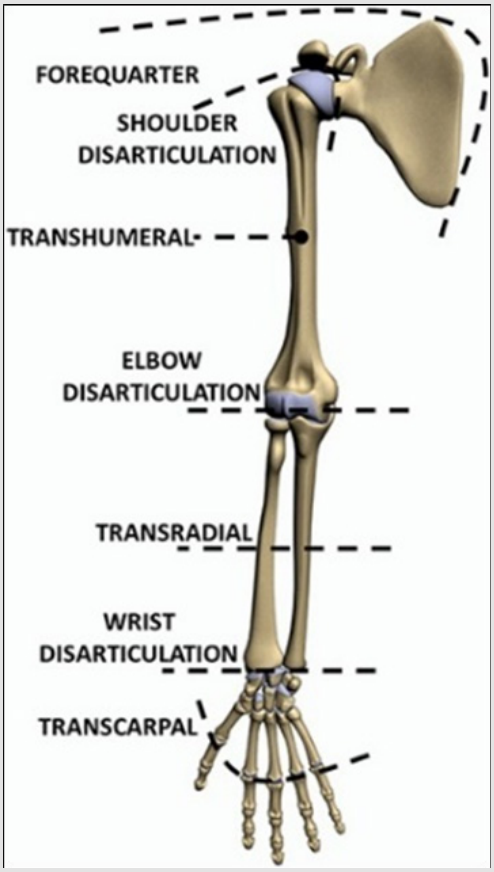

Figure 3: Classifications of upper limb loss [8].

Cause of Upper Limb Loss

The most common cause of upper limb loss worldwide is through trauma. In 2017, roughly 57.7 million people had amputations caused by trauma, of which 19.6% had unilateral and 32% had bilateral amputations. The main causes were road accidents, falls and mechanical force (most likely from machinery) [9]. Someone with unilateral amputation still has the use of one upper limb, whereas a bilateral amputee is missing both. This review is aimed towards people living in the developing world. Ethiopia is considered one of the poorest countries in the world. Berhe G. et al. (2018) list the causes of amputation in this country (Table 1) [10]. The table shows that most amputations in Ethiopia are caused by tumours and Peripheral Arterial Disease (PAD). 11.4% of these were major limb amputations and 17.2% were digital (finger & thumb) amputations. Furthermore, these results show that for people under the age of 15, most amputations were caused by trauma, particularly "Fall Down Accidents" (FDAs).

Table 1: Causes of amputation in Ayder referral hospital, Ethiopia [10].

Cause of Amputation	No. people	Percentage
Tumour	21	24.10%
Peripheral arterial disease (PAD)	18	20.70%
Trauma		
-Fall down accident (FDA)	9	10.30%
-electrical burn	9	10.30%
-Machine injury	5	5.70%
-Road Traffic accident	5	5.70%
-Other	5	5.70%
Infection	8	9.20%
Diabetic foot ulcer	7	8.00%

Figure 4: Satisfaction with Myoelectric Prostheses vs Body Powered Prostheses [12].

Table 2: Prosthesis rates and use of rejection [7].

Prosthesis	Currently used	Previously used	Rejection Rate	Primary Prosthesis	Interested in future use
Adults					
Passive hook	5%	19%	74%	2%	1%
Passive hand	33%	62%	47%	18%	10%
Body powered hook	43%	87%	51%	32%	2%
Body powered hand	15%	43%	65%	3%	3%
Electric hook	13%	21%	38%	3%	13%
Electric gripper	10%	24%	58%	1%	10%
Electric hand	58%	98%	41%	41%	26%
Other	11%	19%	42%	-	11%
None	-	-	-	-	25%
Pediatric					
Passive hook	2%	3%	33%	6%	0%
Passive hand	18%	46%	61%	23%	10%
Body powered hook	12%	23%	48%	14%	2%
Body powered hand	9%	17%	47%	15%	7%
Electric hook	0%	0%	-	0%	8%
Electric gripper	0%	2%	100%	0%	7%
Electric hand	27%	42%	36%	42%	33%
Other	5%	14%	64%	-	7%
None	-	-	-	-	26%

Table 3: Challenging activities report by 178 survey volunteers [7].

Activity	Detailed description	Frequency
Household chores	Repairs and household maintenance (i.e., car repairs, shoveling snow, gardening, electric work); general housework (i.e., vacuuming, dishes, cleaning); use of tools (i.e., hammer, power tools, shovels); heavy lifting; climbing (i.e., ladders)	40%
Sports	Cycling, swinging sports (i.e., golf, baseball, tennis); monkey bars/climbing; swimming; exercising; rock climbing; boating (i.e., canoeing, kayaking); ball sports (i.e., basketball, volleyball)	30%
Hobbies	Playing a musical instrument (i.e., guitar, piano); motorbike and airplane control; woodworking and crafts	22%
Activities of daily living	Food preparation and eating (cutting food, peeling, slicing); dressing (i.e., zippers, buttons, laces, pantyhose, ties); hair styling; typing; washing/personal hygiene; childcare; driving	19%
Social activities	Intimacy (i.e., sex, hugging); clapping; shaking hands; passing through airport security; dancing	8%
Occupational activities	Operating heavy machinery and large vehicles (i.e., farming equipment, trucks, training to be a doctor, surgeon, chemist etc.; law enforcement	6%

Prosthetic Satisfaction and Cause of Rejection

A prosthetic need to replicate a human hand as closely as possible, at least in its function. The prosthetics need to be able to interact with the environment and manipulate objects in the same way as a real hand can. In a world dominated by able bodied people, everything is made with the intention of being manipulated by a human hand [4]. The ideal replacement for a human hand would need to accurately mimic the dexterity, tactile feedback, appearance, and simplicity of use. Myoelectric prosthetics are the most successful solution currently available.

 DOI: 10.26717/BJSTR.2022.46.007289

The anatomical function of a hand cannot be achieved through use of these prosthetics. They have fewer DOFs, typically look robotic in appearance and have low functionality. A survey shows that 30-50% of myoelectric prosthesis recipients do not use their prosthetics regularly because of these problems [4]. Myoelectric prostheses are controlled using electromyographic stimulation (EMG) signals from the remaining forearm muscles [11]. Another active option is body powered prostheses. These are used by unilateral amputees; they are controlled by cables fastened to the users working arm. Myoelectric prosthetics are preferred over body powered as the body powered require a lot of energy from the user. Figure 4 [12] shows a comparison of satisfaction and problems experienced between myoelectric and body powered prosthetics. It strongly suggests that the myoelectric prosthetics are preferred.

Further study was carried out by Biddiss et al. [7] on 242 participants who use prosthetics to explore which types of prosthesis are more commonly used and which are rejected (Table 2). The data can be applied in decision making concerning prosthesis types chosen by amputees. The rate at which paediatric passive hands are rejected is 61%, which is drastically higher than paediatric active hand rejection. This suggests that passive hands are often used as an introductory prosthetic. In adults, the electric hands rate of rejection (41%) is less than the rejection of body powered prosthetics (65%) or passive hands (47%). Nevertheless, the rejection rates did not differ much between adults and children. Both parties show the greatest interest in having an electric hand prosthetic.

While function is important, the cosmetic appearance of a prosthesis is often the first thing in which a prosthetic user will focus [13]. Myoelectric prosthetics are best suited for providing functionality and cosmetic restoration. They best meet the individual's desire to fit in socially and not feel as if they are attracting unwanted attention [14]. Giving a prosthetic a more natural appearance and texture should help the user feel more included in society. A large reason for prosthetic rejection is the need for a harness. They are uncomfortable and discomfort is a big reason why prosthetics are rejected. Harnesses are required for transhumeral prosthetics. However, myoelectric prosthetics reduce the harness discomfort. They do not have as much need for a harness as body powered prosthetics, thus can be worn less tightly and are then less restrictive. This aspect is essential for the user as comfort is such a high priority. The elimination of the harness entirely would make attachment and detachment of the prosthetic easier, especially if the user is clothed [13]. Furthermore, many UL prosthetic users complain that their prosthetic is too heavy, resulting in prosthetic rejection. A heavy prosthetic causes bad posture and inability to operate the arm in a natural style [15]. This project aimed to reduce the weight of the prosthetic as much as possible. However, the product had to remain durable and functional. The heavier grip force generating components should be placed at the rear of the prosthetic to replicate the feeling and balance of a natural arm [16]. By ensuring that the mass of the hand weighs the same as the rest of the prosthetic can provide an even distribution of weight across the arm. This is possible through finite element analysis (FEA) topology optimisation. Another survey by Biddiss, et al. [7] with 178 volunteers, explained the activities found most challenging (Table 3). The survey found the most challenging tasks to do were household chores. All the individuals who used prosthetics consistently reported that they suffered a great number of challenges in their daily life.

Motions of a Hand

The grip strength of myoelectric prosthetic is greater than that of a body powered device. No increased effort is required from the myoelectric user and no concentration is required to sustain the grip with myoelectric control. Myoelectric devices can reproduce the normal grip patterns of a normal hand. The patterns are more pronounced than that of a body powered device [13]. These normal grip patterns are necessary to perform ADLs. The performance of hand movements can be summarised by three classifications; the Cutkosky grasp taxonomy tree (Figure 5) [17], the manipulation taxonomy tree (Figure 6), and the dextrous subclassification tree (Figure 7) [18]. The Cutkosky taxonomy tree can be used to prioritise which grasping movement to use in the design of an upper limb prosthesis. This can be based on the frequency of which of these grasps are used. Figure 8 shows the frequency that different grasping motions are used by a housemaid and a machinist [19]. Figure 8 shows that for different jobs, different grasps are prioritised. The machinist requires a lateral grip 7% more than the house maid. Presumably this is because the machinist needs to use small tools, such as screw drivers or turning on machines. On the other hand, the house maid uses the medium wrap grasp 16% more than the machinist as they will need to use larger tools, such as a mop or a broom more often. Figure 6 and Figure 7 are further subcategories of the Cutkosky grasp taxonomy tree [17]. These trees further describe how the human hand manipulates objects. The motions include translations, rotations and the DOFs of object manipulation.

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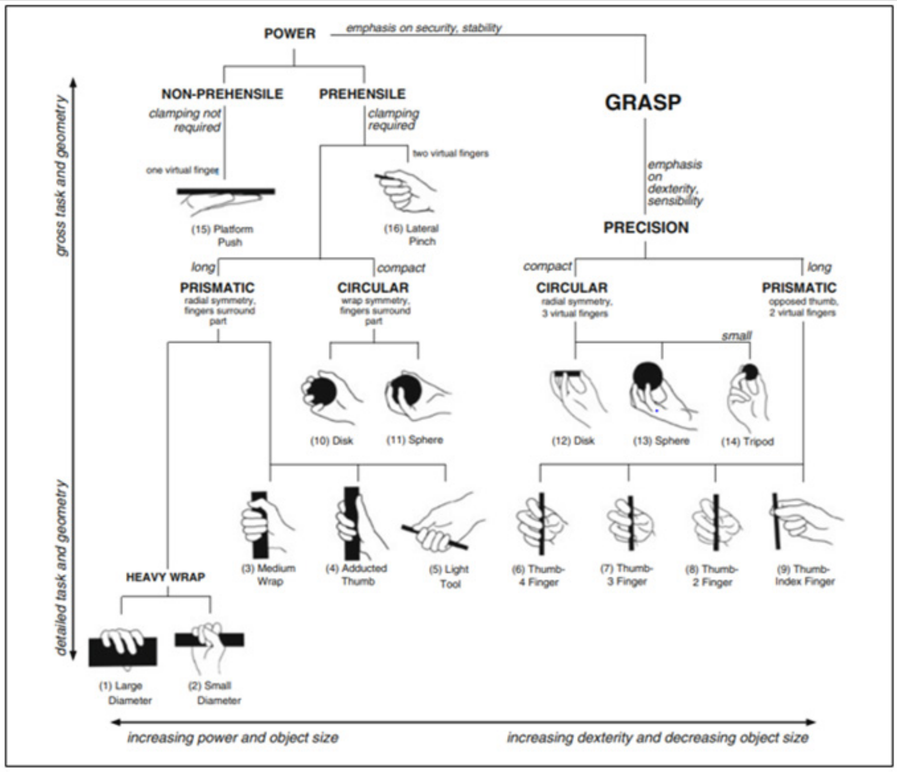

Figure 5: The Cutkosky Grasp Taxonomy tree [18].

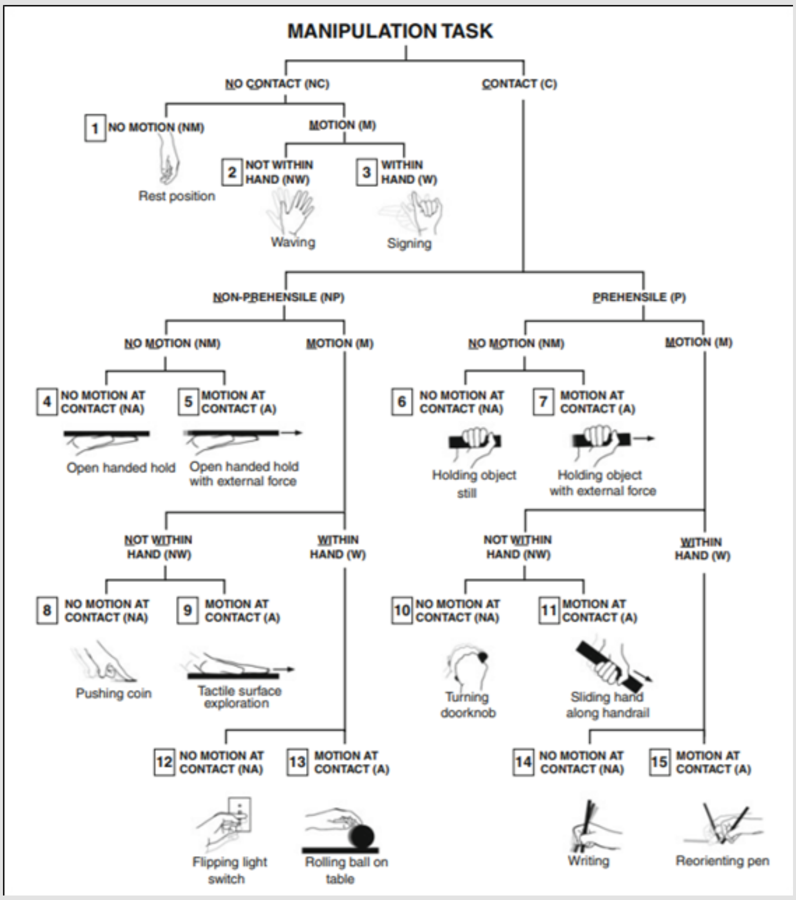

Figure 6: Manipulation Taxonomy Tree [17].

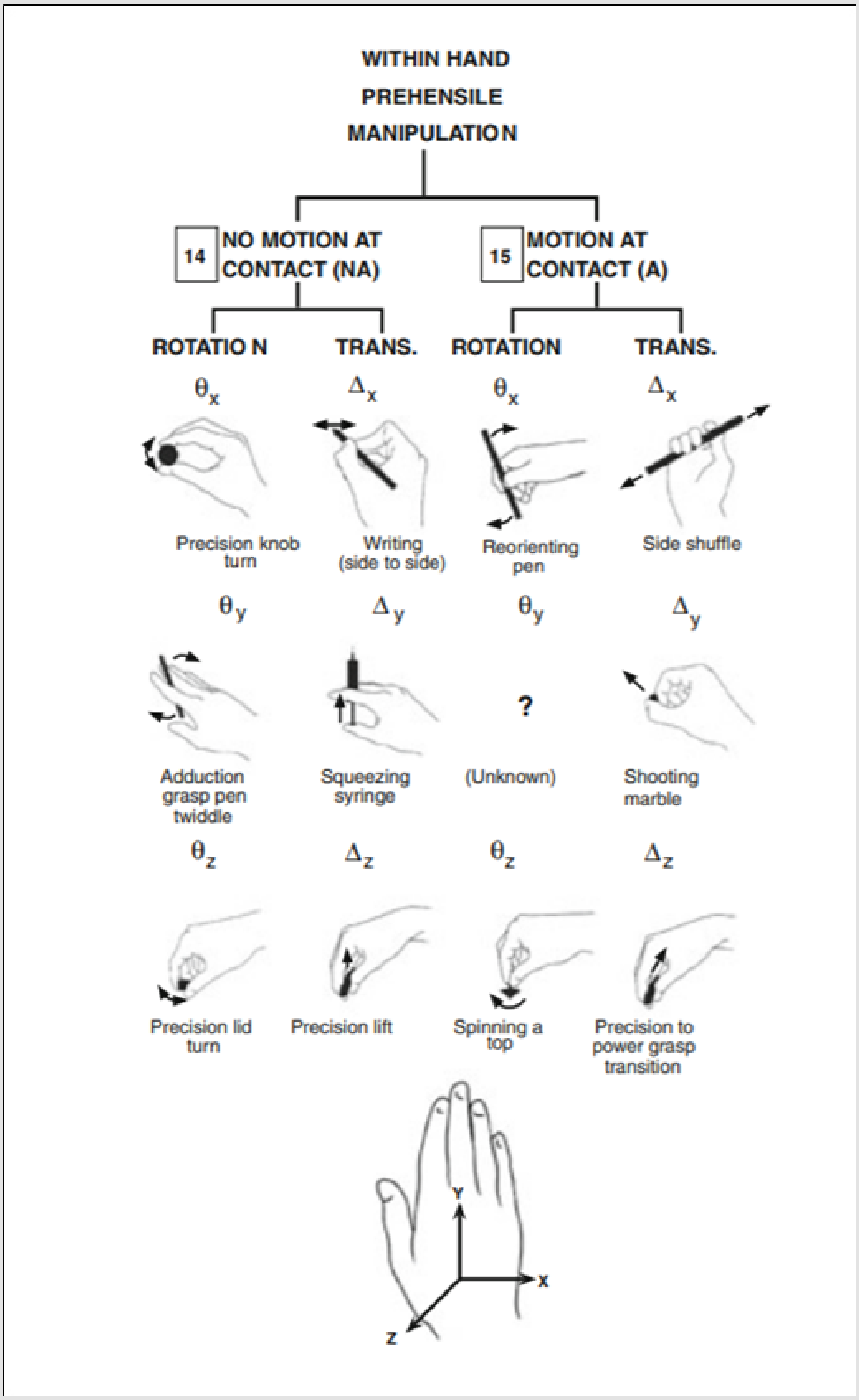

Figure 7: Dextrous subclassification tree [17].

Achieving all the motions shown in these classification trees would be extremely challenging for a prosthetic device. Being able to perform that level of control would require all 5 digits capable of achieving all the DOFs mentioned earlier. This level of movement would only be possible using myoelectric control. The body powered prostheses are too limited in what they can perform without being too strenuous on the user. The myoelectric prosthesis, in theory, can be programmed to reproduce the movements of a real hand. Transradial prosthetics appear easier to programme than myoelectric prosthetics. The stimulation of muscles used for opening and closing the prosthetic hand are the same muscles which are used for opening and closing a real hand. For more extensive amputations, such as trans humeral, the myoelectric sensors use the extensor and flexor muscles that are

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natively associated with release and closure. With targeted muscle reinnervation, it has been noticed that physiological hand function for any level of amputation is very similar to transradial prosthetic control [13].

Prosthetic Design Priorities

Myoelectric prosthetics fall under the category of powered active prosthetics, thus requiring a battery. Users of these prosthetics desire a reliable hand battery. When asked if there were any additional features that could be added to their prosthetic, 60% of people expressed an interest in having a charge indicator for the battery [7]. This same report carried out surveys on 242 participants to determine the consumer design priorities for an upper limb prosthesis. The Table 4 and Table 5 represent the top 10 consumer design priorities for adults and children. For both children and adults, weight is the highest priority for electric and body powered prosthetics. They desire a prosthesis with a better weight distribution throughout the prosthetic. The priorities for adults are the dexterity and functionality of the prosthetic. Children especially had a problem with the heat of the electric prosthetics, claiming that it is too hot against their skin [7]. Donning and doffing are terms used when putting on and taking off a prosthetic respectively. Children find this task frustrating and time consuming. A fragile "pull-in sock" is required to reduce the friction when putting on the prosthetic [20]. A method of attaching the prosthetic without the need for a "pull-in sock" would eliminate this problem.

Table 4: Adult consumer design priorities [7].

Passive hand (n=23)	Pd	Electric hand(n=48)	Pd	Body powered hook(n=37)	Pd
1.Weight	35	1.Weight	45	1.Comfort of harness/ straps	29
2.Fit	31	2.Glove durability	23	2.Weight	23
3.Life-like	28	3.Cost	20	3.Cost	20
4.Heat	17	4.Sensory feedback Fine motor skills/ dexterity	16	4.Wrist movement/ control	20
5.Cost	16	5.Heat	15	5.Grip strength Fit	18
6.Colour Appearance under clothing Glove durability	15	6.Frequency of unplanned movements	14	6.Reliability	16
7. Control of opening/ closing	12	7.Life-like	10	7.Heat	12
		8.Comfort of harness	9	8.Sensory feedback	9
		9.Reliability Size Independently moving fingers	9	9. Ability to maneuver in awkward positions	8
		10.Fit Wrist movement /control	7	10.Donning/doffing Physical effort needed to use	8

Table 5: Paediatric consumer design priorities [7].

Passive hand (n=11)	Pd	Electric hand(n=25)	Pd	Body powered hook(n=9)	Pd
1.Life-like	35	1.Weight	70	1.Weight	36
2. Fine Motor/ dexterity	29	2.Heat	28	2.Overall appearance Overall comfort Overall function	29
3.Ease of cleaning Colour	24	3.Glove durability	23	3.Size	18
4.Heat	16	4.Sensory feedback	21	4.Reliability	13
5. Size Appearance under clothing Weight Glove durability	15	5.Noise	14	5.Life-like Fit Usefulness Harness comfort Ease of control	11
6.Sensory feedback Resistance to moisture/sand/dirt Cost	9	6.Cost	13	6.Heat Grip strength	9

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		7.Life-like	12		
		8.Wirst movement/ control	9		
		9.Size Ease of cleaning	8		
		10. Donning/doffing	7		

Tightening Systems

A solution to this problem is to have the prosthetic tighten onto the user's arm. The BOA lacing system (Figure 9) is a patented design which involves turning a dial which tightens a lace [21]. This can be done with one hand which makes it ideal for unilateral amputees. The technology is typically used in trainers and snowboarding boots however can be used for various applications. The optimisation of these lacing systems is done to maximise the fitting and comfort [22]. A quick pull lacing system is another method of tightening (Figure 10). It is also often used in snowboard boots. It only requires the pull of one lace to tighten the whole system [21]. It is quicker than the BOA lacing system however you must find somewhere to store the leftover lace. The BOA lacing system cannot tighten specific sections, it can only tighten the overall wire. The quick-pull system is more customisable with how it is tightened [23,24].

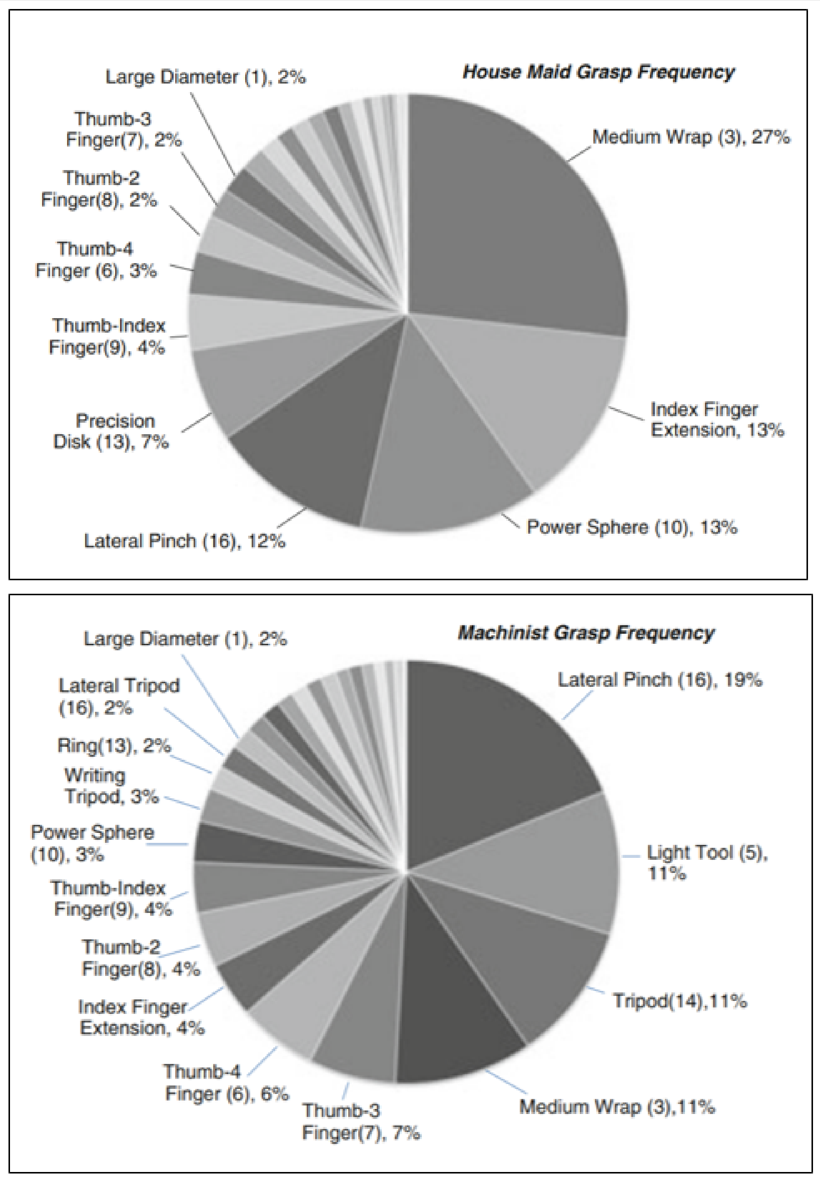

Figure 8: Frequency of grasps for a housemaid and machinist respectively [17].

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Figure 9: BOA Lacing System example [23].

Figure 10: Example of Quick pull lacing system [24].

Grip Texture

Another important aspect of prosthetics is the grip to pick up objects. The grasp motion discussed in the Cutkosky taxonomy tree (Figure 5) has limitations. Texture (Figure 11) and friction of the prosthetic is also important. Material such as leather, silicone, nitrile, and PVC can benefit the grip of the prosthetic. Nitrile is ideal for a 3D printed prosthetic. The nitrile can be applied to the palm and fingertips using nitrile dipping [25]. The perceived weight of an object is lighter when a surface texture is applied. Smoother objects always feel heavier. In terms of the prosthetic, a textured and grippy material will reduce the force required by the digits when lifting an object [26]. There is a wide variety of subject areas to explore when designing for an upper limb prosthesis. The myoelectric approach is the most popular among users, however there are many desirable improvements such as reducing the weight. The weight of the prosthetic can be optimised using FEA topology and 3D printing. Current knowledge aids in prioritising the range of motion to design based on the frequency they are used in different environments. The design should be based around the motions of a real human hand that were classified in the Cutkosky taxonomy tree. Adjustability can be achieved by using tightening systems which attach the prosthetic around a person's arm [27].

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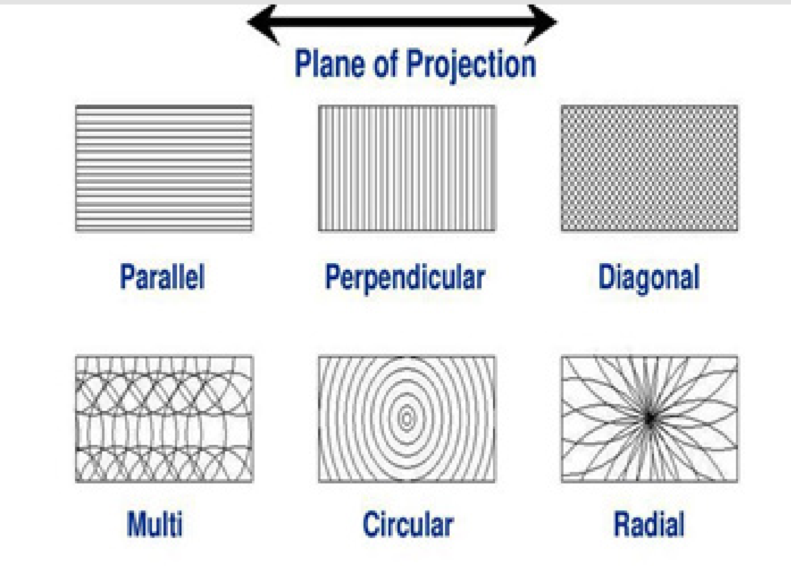

Figure 11: Types of grip textures [27].

Hypothesis

The hypothesis of this project was that a lightweight, affordable, and functional prosthetic could be produced with the use of topology optimisation and 3D printing technology.

Design Methods

Product Comparison

Figure 12: Flexy Hand 2 [29].

Flexy Hand 2 (Steve Wood): The Flexy Hand is a body powered 3D printed prosthetic (Figure 12) [28,29]. The digits open and close with the movement of the wrist. It has very limited control and can only open and close the hand. This product is only designed for metacarpal amputees as the wrist is required for the control. The product is open source which makes it very affordable costing around £50 for the material costs. Of course, it is only this cheap if you already have a 3D printer (roughly £2000), otherwise you will have to pay for the labour costs and markup profit.

Figure 13: BeBionic Hand [31].

BeBionic (Ottobock): BeBionic is the most advanced hand prosthetic on the market (Figure 13). It is for amputees who are missing anything above the wrist. This is possible as the BeBionic hand is made compatible with the other Ottobock prosthesis products. It offers precise control with microprocessors which can change grasp strength. The thumb is anatomically designed so that the most surface area is utilised when grabbing objects. It can perform 14 different gips [30]. They offer three different options; short wrist, quick disconnect wrist and flexion wrist. On top of this, they offer a natural looking cosmetic glove for an extra fee with 8

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skin tone options. The cost of this prosthetic is between $30,000 and $40,000 [31].

Hero Arm (Open Bionics): Open Bionics offer a medically certified 3D printed below elbow prosthetic (Figure 14). It offers myoelectric control of 5 digits and can be customised by the consumer. It cannot be made to look like a human arm; however, they offer different textures and colours as well offering cosmetics to make the prosthetic look like a superhero arm such as ironman. This would be appealing to children. It offers feedback to the user through lights and vibration too make it easier to interact with the environment. Gestures can be swapped by pressing a button on the back of the hand, this could be frustrating for a user [32]. They offer three different pricing plans aimed at different markets. The £9,499 package for adults, the £10,499 aimed at young adults and the £12,699 package for children. All these include a different level of care plan for 36 months. A better care plan is offered with the higher paid packages. The higher packages also include "OB coins" which can be used to purchase cosmetics for your prosthetic and extra clinical appointments. These extra cosmetics and covers cost between £200 and £300 [33,34].

Figure 14: Hero Arm [33].

Figure 15: True Limb [34].

True Limb (Unlimited Tomorrow): True Limb offers a fast and affordable 3D printed prosthetic (Figure 15). It can all be done online; they send the customer a 3D scanner to scan their arm so that the prosthetic can be designed specifically for their needs. It offers 6 different grips and conforms to any object it comes in contact with. However, the thumb cannot contact every digit on the hand. This prosthetic has a more natural look and offers a large range of skin tone colours. The prosthetic costs around £7,995. It uses Nylon PA-12 for to increase its strength and durability. It is controlled with muscle sensors and has vibration feedback when it makes contact with an object.

Determining the Ideas

This section will discuss the engineering steps behind the final design. The literature around the need and design of prosthetics provided the central background knowledge and understanding for who, where and why affordable prosthetics are needed. This focus propelled the project forward starting with a Quality Function Deployment (QFD) (Figure 16). The QFD is an important tool to prioritise consumer requirements found in the literature and choose engineering requirements to satisfy the needs. It also includes a comparison between the current products. The most important consumer requirements were "Cheap to purchase" and "Safe to use". This project is aimed towards those living in developing countries. People living in these countries can rarely afford the prosthetics currently on the market. Therefore, the prosthetic must be made affordable to them. Furthermore, the product must be safe to use and satisfy ISO safety regulations. Other consumer requirements such as "Adjustable for different users" and "movement for ADLs" are ranked highly as these are the minimum functions that the prosthetic should provide. Costing, adjustability, and movement will be highly influenced by the number of components. A higher number of components will allow for greater degrees of freedom but will also increase the price.

The QFD formed the foundations for a morphological analysis (Table 6). The morphological analysis is used to explore all possible solutions to a non-quantified problem. This method aims to create the best possible design solutions from research which satisfy the requirements displayed in the QFD. The highest scoring engineering requirement from the QFD was a universal hand to arm attachment and the number of degrees of freedom. The universal hand attachment was not mentioned in the morphological analysis as further research was required at the time. It was decided to focus on transradial prosthetics as to focus mainly on the functionality of the hand movements. The analysis above satisfies the QFD by using commonly used techniques and techniques learnt in the literature. Having more degrees of freedom in the digits is better in theory, however, is much harder to design with myoelectric control in mind. From this analysis, 5 design ideas were created for the prosthetic (Table 7).

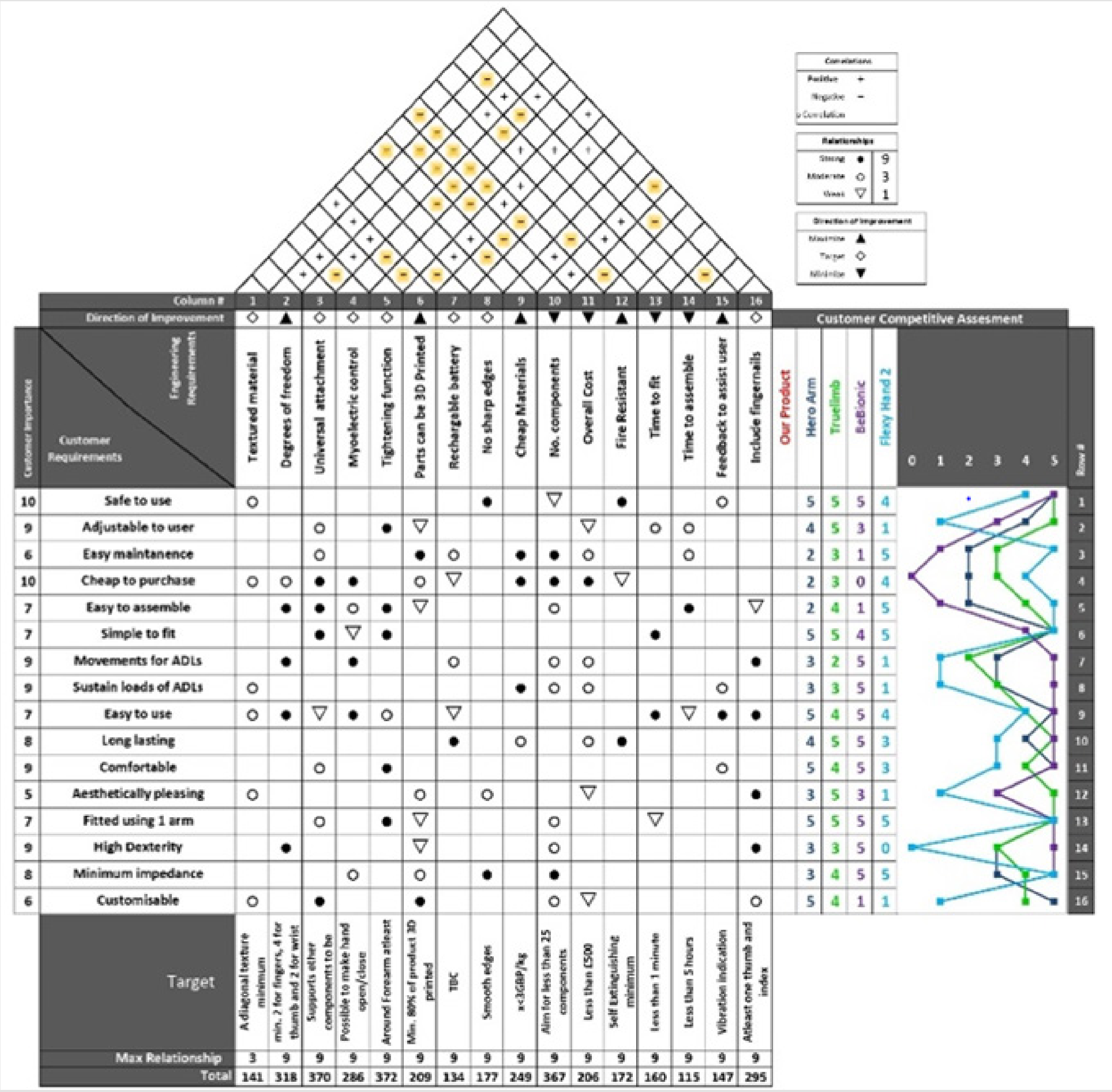

Figure 16: Quality Function Deployment.

Table 6: Morphological Analysis.

Feature	1	2	3	4
Metacarpal Joint	Hinge	Ball	Knuckle joint	
Phelangeal Joints	Hinge	Ball	Knuckle joint	
Thumb DOF	2	4	6	
Finger DOF	2	4		
Wrist DOF	2	4	6	
Number of Digits (Including thumb)	2	3	4	5
Finish	Nitrile	Latex	Rubber	None
Power Method	Myoelectric	Body Powered	Electric	Mix

Fingernails	2	3	4	5
Carpometacarpal joints	Inwards hinge	Ball Joint	Saddle Joint	
Fingertip texture	Diaganol	Multi	Circular	Radial
Fitting method	Scalable size	Closing design		
Tightening method	Boa Lacing System	Quick null lacing system	Power Stran	Ski Boot Buckle

Table 7: Design Ideas from Morphological Analysis.

Feature	Idea 1	Idea 2	Idea 3	Idea 4	Idea 5
Metacarpal joint	Ball	Knuckle Joint	Ball	Knuckle Joint	Hinge
Phelangeal joints	Hinge	Knuckle Joint	Knuckle Joint	Knuckle Joint	Hinge
Thumb DOF	4	6	4	4	4
Finger DOF	2	4	2	2	2
Wrist DOF	4	6	4	2	2
Number of Digits	5	5	3	4	3
Finish	Nitrile	Latex	Rubber	Nitrile	Latex
Power Method	Myoelectric	Mix	Body Powered	Myoelectric	Electric
Fingernails	3	5	2	3	2
Carpometacarpal joint	Inwards Hinge	Saddle Joint	Ball Joint	Inwards Hinge	Ball Joint
Fingertip texture	Diaganol	Circular	Radial	Circular	Multi
Fitting Method	Closing design	Scalable	Closing design	Closing design	Scalable
Tightening method	Quick Pull Lacing system	Power strap	Boa Lacing system	Boa Lacing system	Ski boot buckle

Idea 1 in the table suggests using 5 digits with the thumb joint as an inwards hinge and fingers joined with ball joints. The ball joints will allow for a full range of motion in 2 DOFs. The ball joints will be hard to control with the myoelectric power method suggested. Idea 2 also offers 5 digits however using knuckle joints. The use of a saddle joint allows thumb to move in 6 DOFs. The saddle joint will be hard to design. The mix of power methods would combine myoelectric, and body powered. The body powered would be used when the movements required are too complex to code. Having 6 DOF in the wrist would be very complex to design and not necessarily required, thus this idea was dismissed. Idea 3 is made with 3 digits using a body powered approach. There are many complaints about body powered prosthetics being too uncomfortable, so this idea was dismissed. Idea 4 uses 4 digits with knuckle joints for the fingers and an inwards hinge for the thumb. This inwards hinge will allow for greater dexterity. This idea also uses the much-preferred myoelectric power method found in the literature. Finally, Idea 5 uses 3 digits. The thumb is mounted using a ball joint giving it high degrees of freedom. The design may not allow for great dexterity due to the small number of digits. As Idea 2 and 3 were dismissed, the other 3 ideas were further developed into initial concepts which could satisfy the aim of this project.

Initial Concepts

The initial concepts were designed using ideas 1,4 and 5 from the morphological analysis. From this point Idea 1 will be referred as Concept C, Idea 4 will be Concept A and idea 5 will be Concept B. These concepts were hand drawn and focus on what features will be on the prosthetic. The concepts help to visualise each idea and where each feature will be situated. Concept A can be seen in Figure 17. It makes use of a 4-digit design with radial grip textures on the tip of each. This radial grip texture will help grip objects. As mentioned in the literature this grip will make heavy objects perceive to be lighter. This grip is further advanced by the nitrile covered tips. This can be applied using nitrile dipping on the fingertip components. The radial texture has been applied to the palm of the hand as well because larger objects will contact these areas when being grasped. Each finger is given three joints, like the real human hand. The thumb also moves true to a real thumb due to the inwards facing hinge. This hinge allows the thumb to contact each finger allowing a full range of dexterity. As only knuckle joints are used, abduction and adduction will not be possible in the fingers. Abduction and adduction would be hard to programme in the myoelectric control suggested.

To tighten the prosthetic to the user's forearm, a Boa lacing system is used. This is a patented design which can be purchased and used to attach the prosthetic quickly and easily. The simple dial can be turned using one arm, thus making it ideal for this type of application. As the prosthetic will be made using 3D printing, the polymer used will not be flexible. If this design were used the forearm component would need to be designed with moving parts which will grip to the user. Concept B (Figure 18) makes use of a 3-digit design with a multi grip texture applied to the tip of each. This more simplistic approach would be better for gripping heavy

 DOI: 10.26717/BJSTR.2022.46.007289

objects and would be much quicker to assemble once it has printed. This concept would be controlled using an electric approach. The button on the back of the forearm would control the opening and closing of the hand. This would certainly be the easiest concept to programme. The fingers have 3 hinges which mimic finger joints in a real hand. These hinges would lower the safety of the prosthetic as it would raise and lower the back of the fingers. This could lead to potentially pinching objects, clothing, or other people (perhaps during a handshake) in the hinge. Extra parts would be required to act as a barrier at the back of each joint to prevent this. The ball joint at the base of the thumb gives it a full range of motion. This ball joint would be difficult to programme, especially with control of a button. More controls would need to be added for this to work.

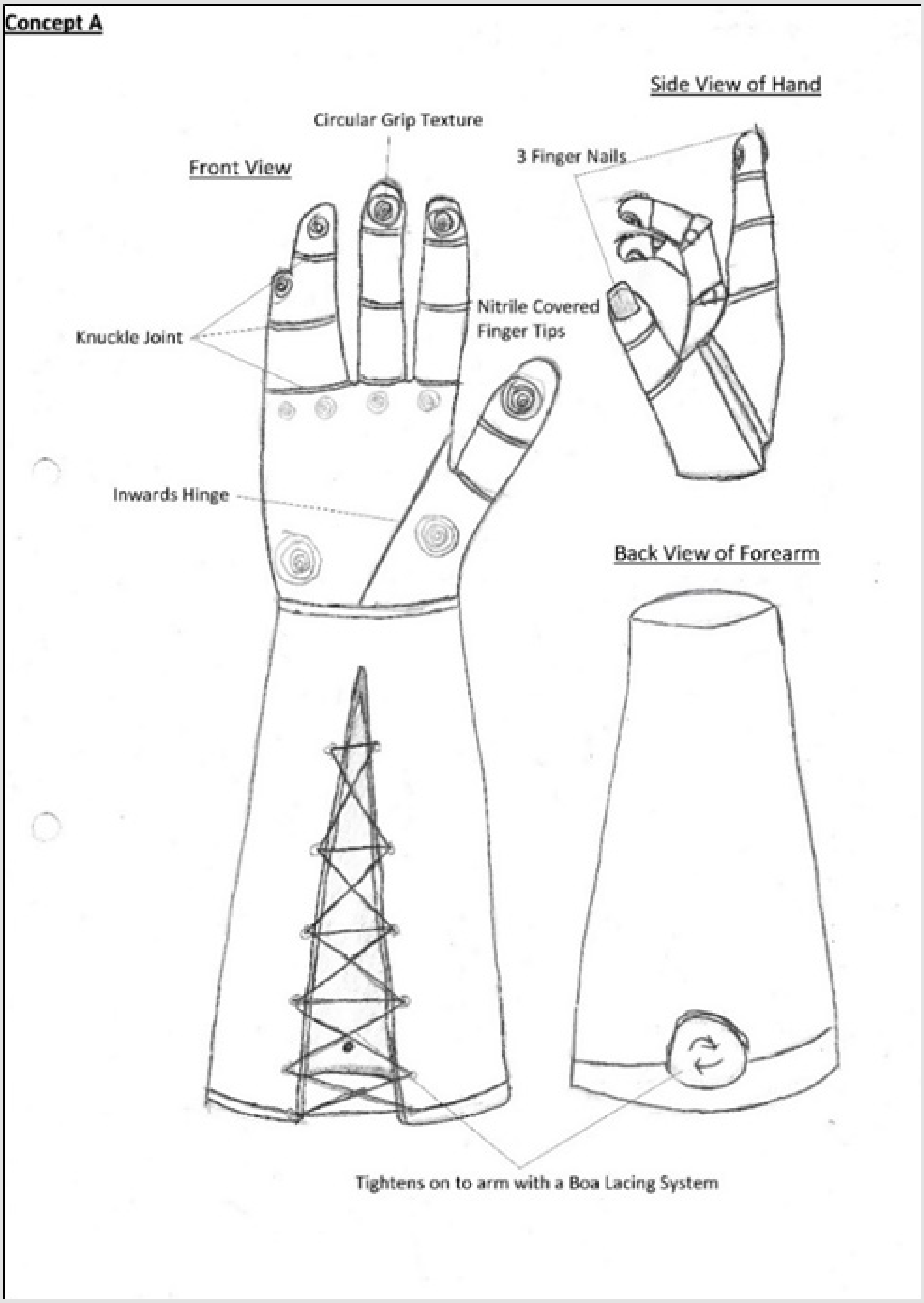

Figure 17: Concept A (Idea 4).

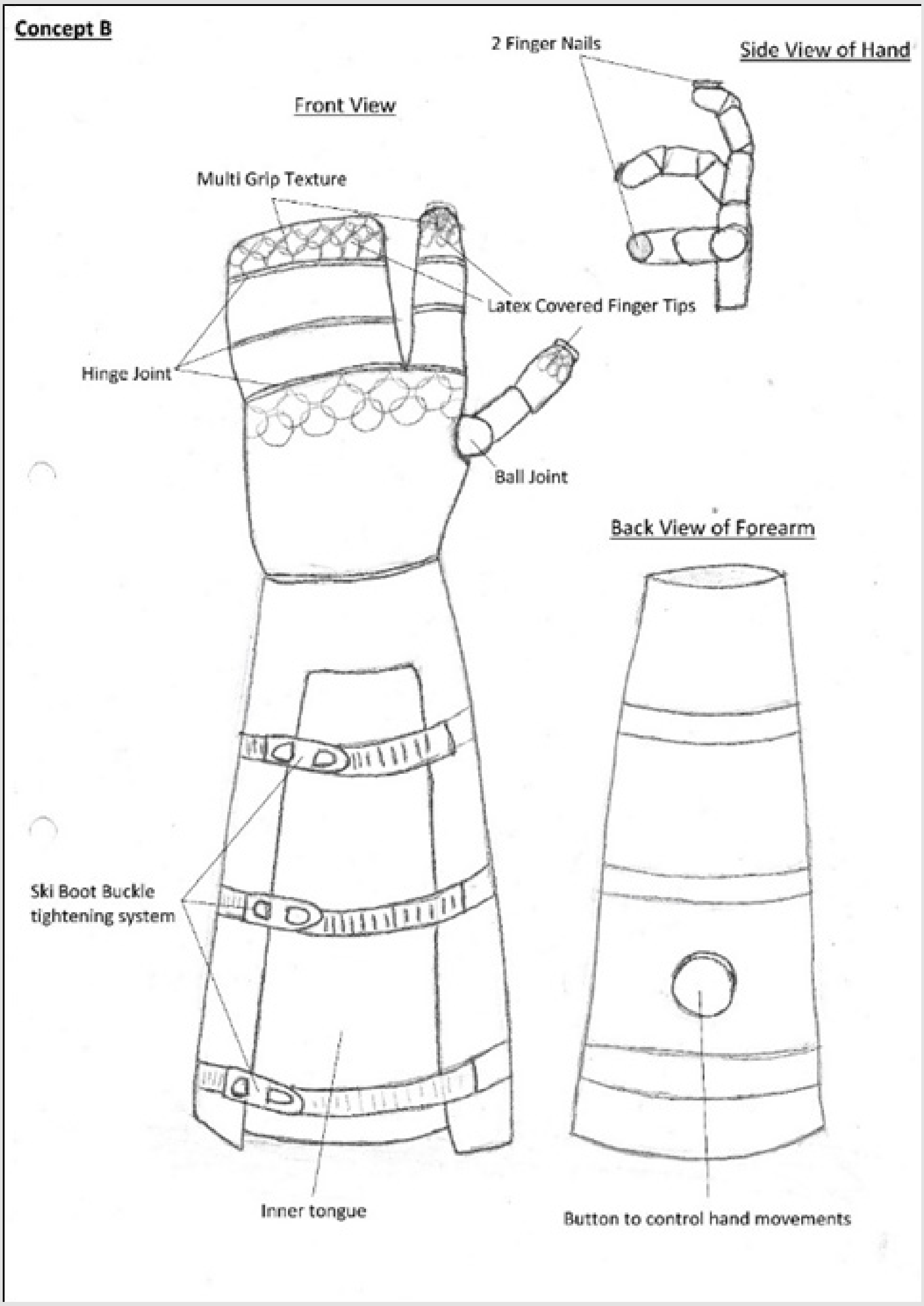

Figure 18: Concept B (Idea 5).

The prosthetic is tightened to the user with ski boot buckle design. These are otherwise known as ratchets. Again, these can be tightened using one hand making it ideal. The inner tongue is pulled tight against the user's forearm. This inner tongue is hinged to the top of the forearm component. With 3D printing this can be made as one component with the rest of the forearm part. The top of the inner tongue can be made thinner allowing it to revolve. It is not as simple or quick as the Boa lacing system, but it is easier to integrate. Concept C is a design which attempts to be as close to a real human hand as possible (Figure 19). It has 5 digits with a diagonal grip texture. The diagonal grip texture would be the easiest to design. Once again, the fingertips would be nitrile dipped for extra grip. The use of 5 digits makes this design the truest to a real human hand. This is what prosthetics user really want; however, this makes programming the hand much more complex. The pinkie finger is rarely used in day-to-day life other than for support.. Furthermore, the ball joints at the base of each finger will allow for abduction, adducting, extension, and flexion. This would be very hard to programme with the myoelectric control. To counteract the complexity of this design, hinge joints were used for the phalangeal joints. This shares the same problem of safety as concept B but can be solved in a similar manner.

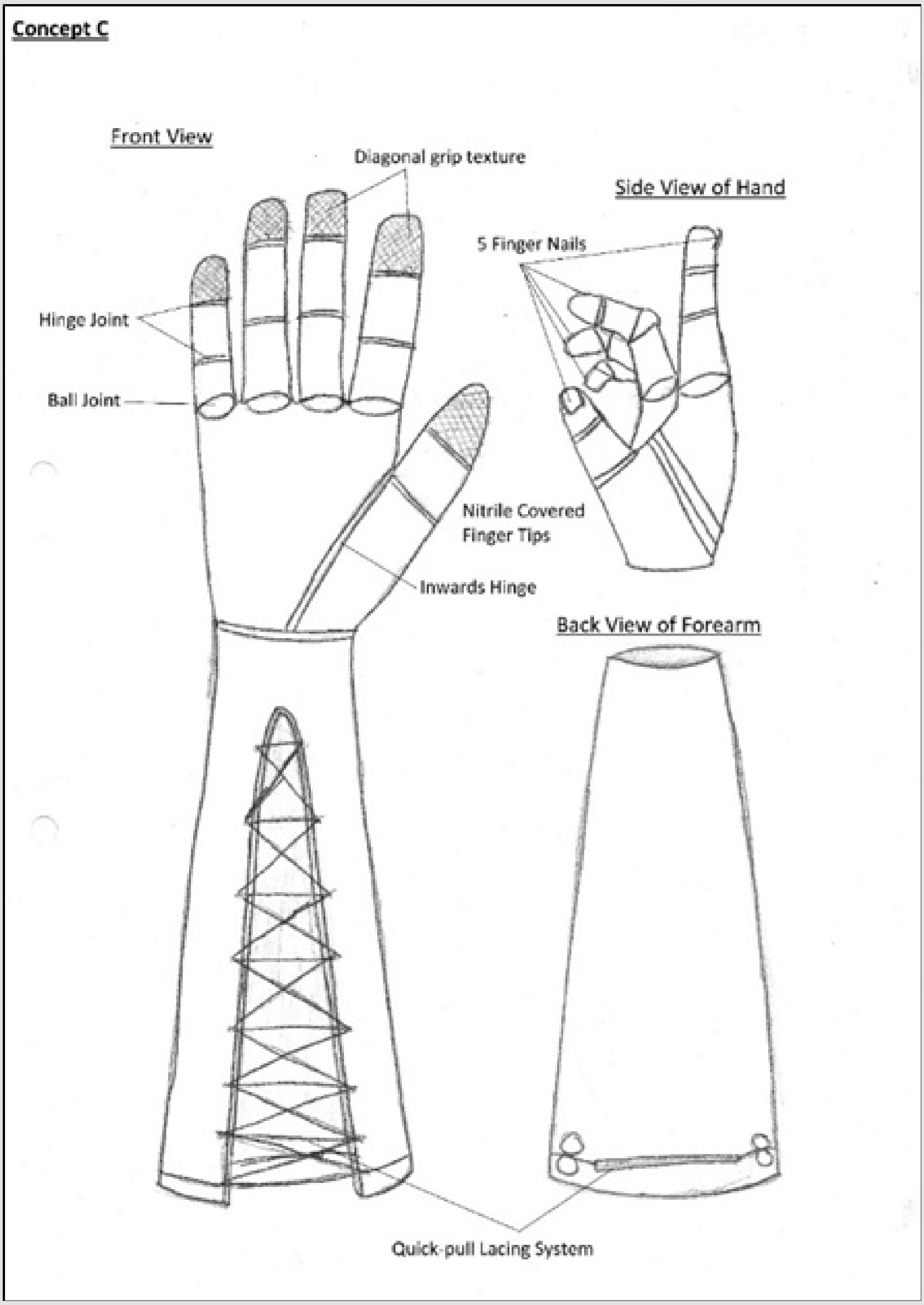

Figure 19: Concept C (Idea 1).

The inwards facing hinge for the thumb is used once again for great dexterity. The pinkie (little) and ring finger might be difficult to contact the thumb. These two digits could have their own inward facing hinge joints added to make this possible. This would then allow for a full range of manipulation. This could have overcomplicated the design though and the design had to be completable within the 13-week time frame. The prosthetic is tightened using a quick pull lacing system. Once again this can be tighten using one arm. This is the fastest approach to tightening the prosthetic. However, you are left with the handle and leftover "string" hanging off the back of the forearm. A pocket for the handle and string would need to be designed so it does not get in the way as it could get caught on objects. Again, the quick-pull system would not work with the non-flexible 3D printing polymer. Thus, an extra flexible part will need to be added to the design which can be tightened.

Criteria	Priority Vector (PV) for Criteria	Sub-Criteria	Priority Vector (PV) for Sub-Criteria
Cost	0.225	Maintenance Cost	0.250
		Production Cost	0.750
Quality	0.138	Tolerance	0.500
		Finish	0.500
Performance	0.155	Easy to Handle	0.042
		Durability	0.284
		Adjustability	0.149
		Safety	0.525
Manufacturability	0.175	Easy to Manufacture	0.500
		Easy to Assemble	0.500
Grip	0.025	Effectiveness	0.25
		Ease to 3D print	0.75
Simplicity to fit	0.040	Speed	0.25
		Ergonomic	0.75
Comfortable	0.046	Lightweight	0.792
		Lining	0.208
Ease of Use	0.076	Method of movement	0.833
		Range of movement	0.167
Movement for ADLs	0.119	Number of digits	0.800
		Degrees of Freedom	0.200

	Design A	Design B	Design C	
SUM	0.3105	0.3877	0.3018	*Preference* P_I
Ranking	*2*	*1*	*3*	

Figure 20: Analytical Hierarchy Process.

Chosen Design

To pick the best concept which satisfies the aims and objectives an analytical hierarchy process (AHP) was created (Figure 20). The AHP was made with the assumption that all the features stated in the morphological analysis were applied for each concept. The AHP refers to the concepts as designs (Concept A = Design A, etc…). The AHP determined that Concept B was the best with a score of 0.3877, followed by Concept A with a score of 0.3105 and finally Concept C scored 0.3018. The AHP gave a comparison between each concept for the most important criteria for an upper limb prosthetic. The first step was determining the priority vector for each criterion. As the prosthetic needs to be supplied in developing countries, the most important criterion was determined to be the cost of the prosthetic. Concept B scored highest for both sub-criteria (maintenance and

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production cost), therefore this had a big influence on the final scores. The second most important criterion was found to be the performance of the prosthetic. This was split into 4 sub criteria with safety being the ranked most important. This correlates with what was discussed in the QFD. With the changes discussed with hinges in concept B and C, all three concepts scored the same for safety. Thus, this sub-criterion had no influence on the final scores. The grip of the prosthetic was given the lowest priority vector as this would be the easiest to implement into each of the concepts. Having a high dexterity for the fingers needs to be designed first for the grip to be any use. Since the project has progressed, in hindsight the movement for ADLs should have been given a higher priority vector. The degrees of freedom and number of digits are very important for the dexterity of the prosthetic. As concept C scored the highest for these criteria this would have changed the ranking of the concepts. This was considered when creating the final design. One of the objectives for this project is to design an upper limb prosthetic which satisfies the most important consumer requirements. An important requirement is a high level of dexterity in the design. Despite Concept B scoring the highest preference ranking, it would not satisfy this high level of dexterity. To resolve this, the final design was a combination of all three designs. For instance, taking the myoelectric control from Concept A and C, the number of digits from Concept A and the ratchet tightening method from Concept B.

Materials

The performance indices for the material selection process were as follows (Figure 21). The first stage was to set a limiting factor which would only consider polymers capable of additive manufacturing. The second stage (Figure 21a) was a beam in bending $(\frac{\rho}{E_{f}^{1/2}})$ vs tie in tension (ρ/E). For these the free variables were section area and shape and the fixed variable was length. For the prosthetic, both these need to be maximised.

The third stage (Figure 21b) was comparing price per unit volume against the resistance to yield against a blunt object $(\frac{H^3}{E^2})$. In this case the fixed variable was contact radius. The price was set to be minimised while the resistance to yield was set to be maximised. As the prosthetic needs to be lightweight, density against price per unit volume were used in stage 4 (Figure 21c). The density and price were set to be minimised. Finally, in stage 5 (Figure 21d), the general yield strength was compared against the price per unit volume as the prosthetic needs to be capable of carrying heavy mass. Thus, yield strength was set to be maximised and price set to be minimised. The final materials can be seen in Figure 21d.

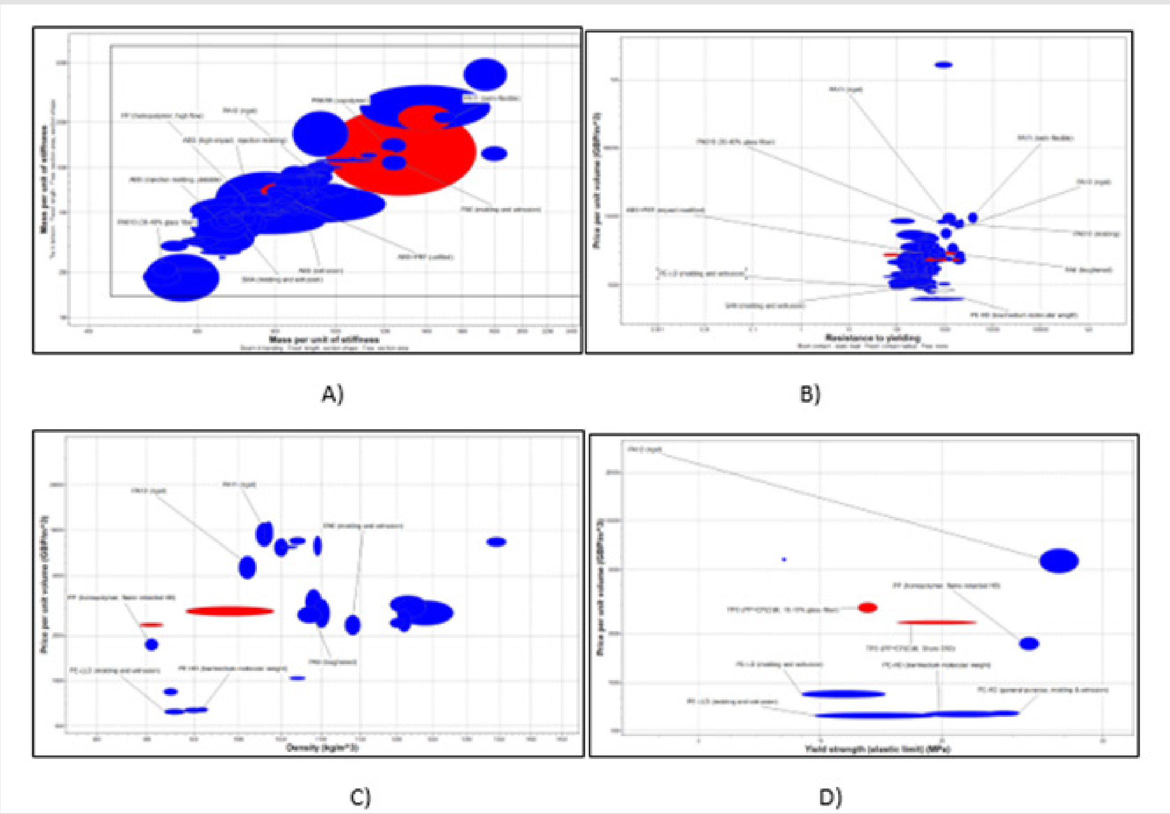

Figure 21: Material Selection Graphs [41].

 DOI: 10.26717/BJSTR.2022.46.007289

After speaking to Sam Gribben, an expert engineer in 3D printing at a company called SGD 3D, he suggested the use of Nylon PA12 for the prosthetic due to its durability and low density. It is ideal for this application due to the complex shapes of each component. The overhangs present in this design usually require extra support material deposited underneath, however with Nylon PA12 less support material is required. This means less finishing is needed once the printing is complete. The typical uses of Nylon PA12 is for precision engineering components [35]. Nylon PA12 is also a commonly using material used in 3D printed Prosthetic design [36]. Some properties of Nylon PA12 are visible in Table 8.

Table 8: Nylon PA12 Properties [41].

Youngs Modulus: 1.08 - 1.35 GPa	Flexural modulus: 1.17 - 1.2 GPa
Density: 1e3 - 1.02e3 kg/m^3	Poisson's ratio: 0.406 - 0.422
Yield strength: 34.8 - 43.4 MPa	Hardness – Vickers: 11 – 12 HV
Tensile strength: 45 – 55 MPa	Fracture toughness: 3.18 - 3.52 MPa.m^0.5

Final Design Process

The Final Design before Topology

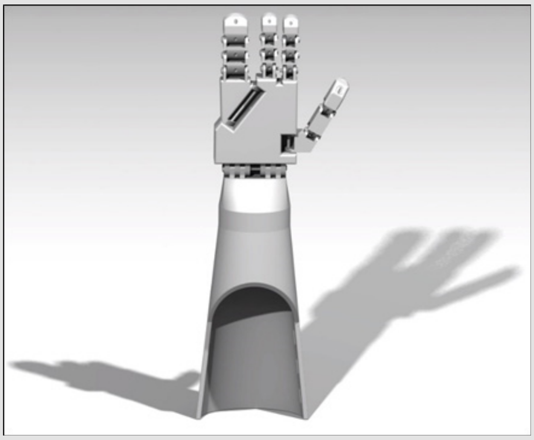

Figure 22: Final design with no topology.

The final design was created in CATIA V.5. Figure 22 shows a render of the prosthetic before topology optimisation was performed. The chosen design uses aspects from concepts A and B. It uses the 4 digits with radial grip texture and knuckle joints from concept A, while taking the ratchet tightening system from concept B. This was decided because concept B ranked highest in the AHP because of its simplicity, however it did not provide the dexterity required for a lot of ADLs such as buttoning a shirt. Taking advantage of 4 digits can solve this. This final design also uses Nitrile material on the palm and digit-tips. As you will see in Figure 24. Figure 22, the palm is removable so nitrile dipping will be easy to do. Each digit-tip can be nitrile dipped before assembly. Nitrile was chosen over latex as many people are allergic to latex [37] and nitrile is now a lot more commonly used [38]. The knuckle joints in each finger rotate around 3D printed pins which will be secured in place with a threaded nut. This way they will be removable for repairs and such. The pins in the current CAD model do not include the thread, thus for the protype these pins will be attached with adhesive. To further improve the dexterity of the prosthetic, the ring finger (4th digit) was attached to the palm with an inward facing hinge and the thumb (1st digit) was allowed to pivot around the horizontal Z-axis so it can reach across the hand (Figure 23).

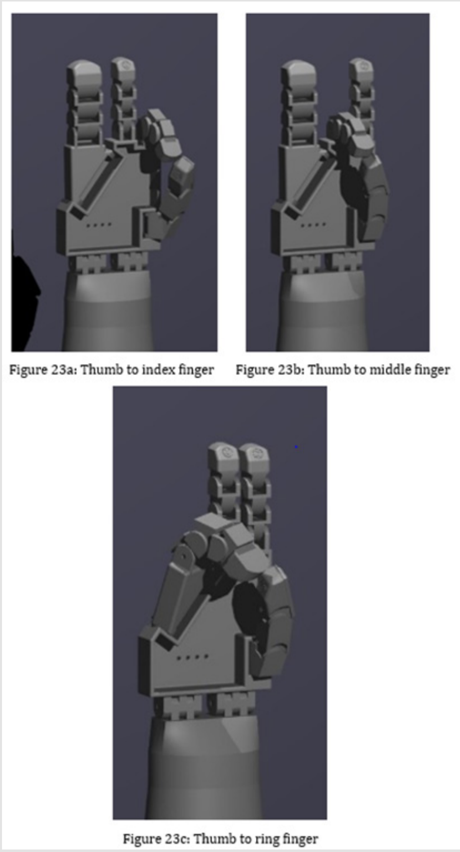

Figure 23: Dexterity of prosthetic.

The palm of the prosthetic is hollow with a removable panel (palm cover) which gives access to the inner mechanics. 0.4mm nylon wire is thread through 3mm holes in each digit, then run through the palm (Figure 25) and out through the back (Figure 25). Elastic bands are attached to the pins on the back of the hand to extend the digits and wrist. Elastic bands were chosen as they are cheap and readily available if they need replaced. A purple material was applied to these figures below as it showed more details than the white plastic material used in the other figures. The hand can

 DOI: 10.26717/BJSTR.2022.46.007289

be detached from the forearm component (Figure 26). This could be for maintenance of any of the components, a replacement should either the hand or forearm become too damaged, an upgrade if a newer improved hand design is made or for attaching a different type of prosthetic. This also adds to the adjustability of the prosthetic. The size of the forearm can be scaled for different users. This is simply done by changing three dimensions within CATIA V.5. This is also useful for young children who are still growing. Rather than having to consistently buy a brand-new prosthetic as they get bigger, they only need to replace the forearm component which is a lot cheaper. The forearm attaches to the wrist using a bayonet fitting. This fixes the wrist component vertically and then a bolt is inserted to stop the wrist twisting. This bolted connection is not visible in the figure as this was thought of after the prototype was made. This component will need a few other changes in future so that the servo/stepper motors and batteries can be attached.

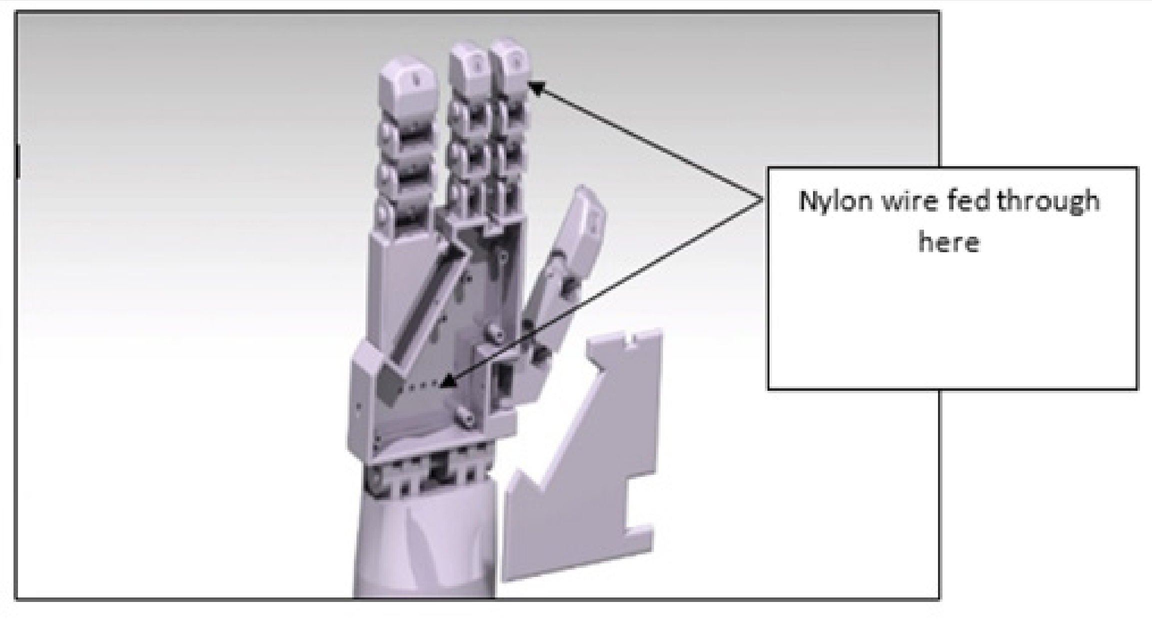

Figure 24: Front mechanics of prosthetic.

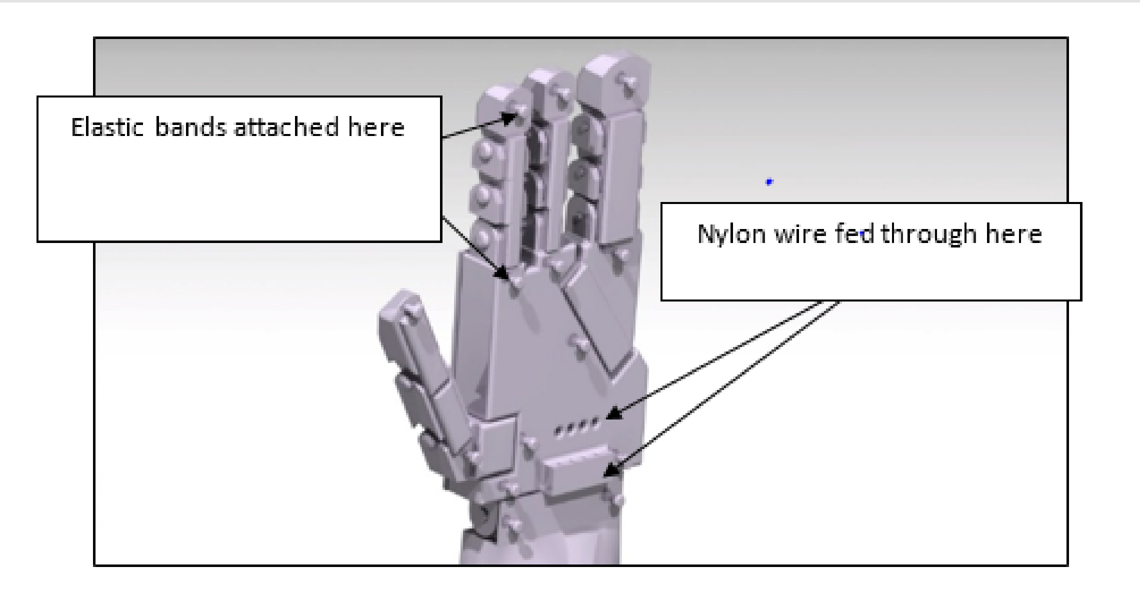

Figure 25: Back mechanics of prosthetic.

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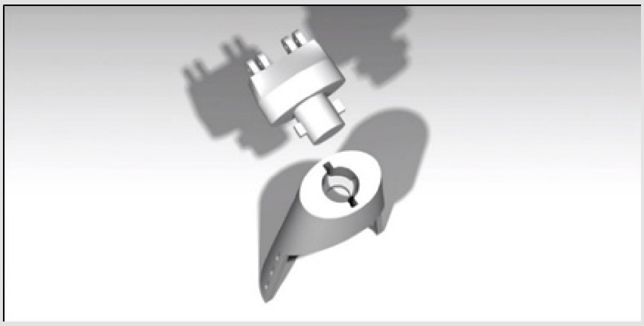

Figure 26: Detachable wrist.

The CAD Design Process

The CAD design was divided into 6 mechanisms. The forearm component, the wrist, the palm, the thumb, the index/middle finger, and the combined ring and pinkie finger.

The Forearm and Wrist Component: The forearm component was the first to be designed as a topology optimisation was to be performed on it (this will be shown later in this chapter). It is comprised of only one component with a current mass of 0.205kg (Figure 27). The forearm was designed as half an elliptical cone shape with a solid cone at the top for the wrist component to be inserted into. As previously mentioned, the top of the forearm has a bayonet fitting designed into it. The rectangular holes seen are there to insert the ratchet tightening system (Figure 28). This component needs to be comfortable, lightweight and have good purchase on the user's arm. Further research and design are required to improve this. Currently the plastic makes direct contact with the arm, this plastic needs a soft lining applied. Different amputees have different shaped stumps. Memory foam could be used at the top of the interior side to mould to these different shaped stumps and maximise comfort. The wrist mechanism is also made from one component Figure 29 [39]. This component is used to clip into the hand into the forearm and pivot the hand. The component sits flush when attached to the forearm.

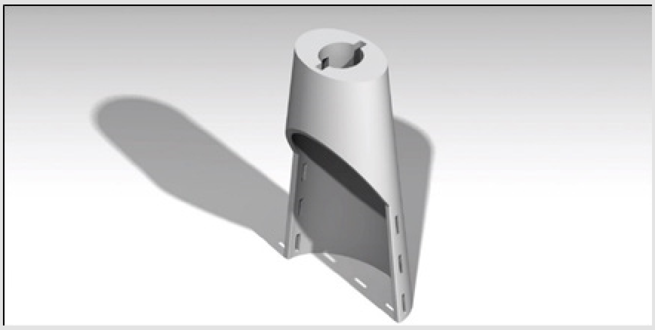

Figure 27: Forearm component before topology.

The Palm: The palm is made up of two components: the palm and the palm cover (Figure 30). The palm is hollowed to reduce the mass and it means the nylon wire, which controls the digits, can be hidden inside the hand. This prevents the wires getting caught and it is more aesthetically pleasing. An interference fit between the pins attaches the palm cover to the palm. Screws will be added into the final design to fix it in place as this palm cover will be rarely removed. The female pins inside the palm also guide the nylon wires towards the exit holes. There is an exit hole for each digit, this is to prevent the wires tangling and makes it easier to organise when attaching them to servo motors.

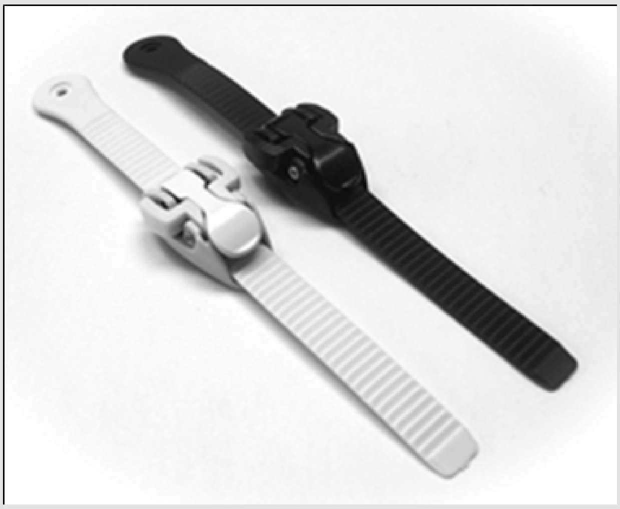

Figure 28: Ski boot ratchet [38].

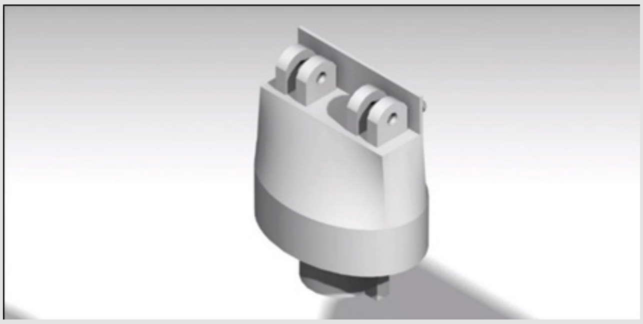

Figure 29: The wrist component.

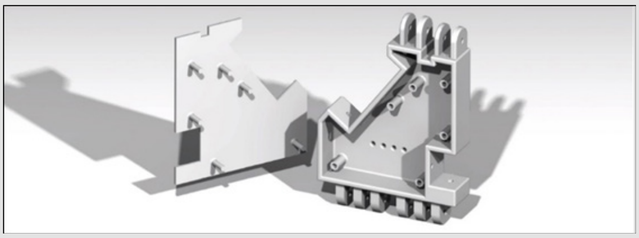

Figure 30: Palm and Palm cover.

The Thumb: The thumb is made of 3 main components with 3 pins holding each part together (Figure 31). The back of the thumb components is straight to prevent the thumb from bending backwards (Figure 32). An opposable thumb is the most

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important digit in the human hand [40]. The base of the thumb was attached vertically for this precise reason (Figure 33). It allows for opposition of the thumb, this way the thumb is rotated so that the pulp faces that of the fingers and the nail can be parallel to the palm (Figure 34) [41]. This replicates the movement of a real human thumb. Including a nail to the thumb tip was important for picking up small objects such as coins [8]. Currently the thumb is controlled by a single nylon wire running throughout the centre of each component. This needs to be changed so that the opposition movement is controlled independently to the flexion and extension. This will allow the thumb to remain extended while travelling across the palm to contact all the digits.

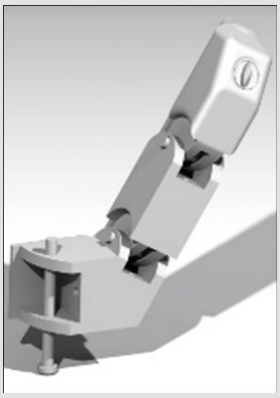


Figure 31: Thumb Front.

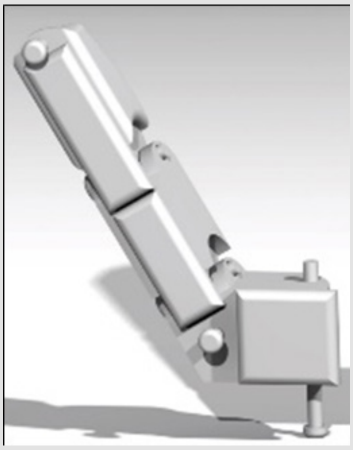


Figure 32: Thumb Back.

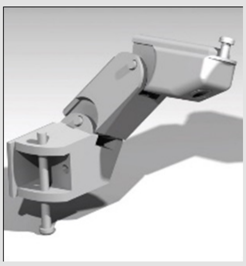


Figure 33: Thumb Closed.

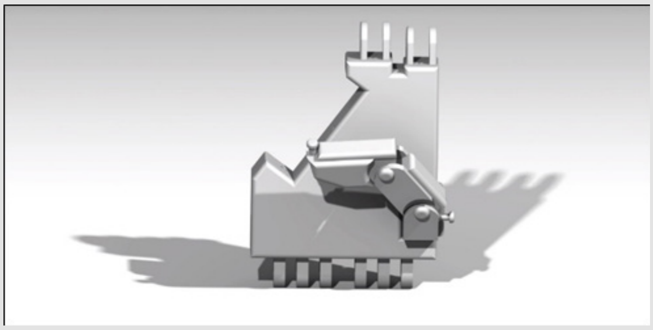


Figure 34: The Opposition of the thumb.

The Index/Middle Finger: The index and middle finger of the prosthetic are made from the same 3 main components (Figure 35). The palm raises the middle finger up slightly to give a more realistic appearance compared to a real hand. The aim with this design was to ensure that these digits could contact the thumb to perform precise thumb-index and thumb 2 finger grasp motions displayed in the Cutkosky grasp taxonomy tree (Figure 5). Figure 23 a and b show that this was successful. The back of the digit is done in the same manner as the thumb to prevent over extension (Figure 36). As knuckle joints were used for these digits, only extension and flexion are possible (Figure 37). The joints prevent adduction and abduction however this will make the myoelectric control easier to programme. These digits would have benefitted from being longer as they only reach halfway down the palm (Figure 38). This works for precise grasps as mentioned earlier, however grabbing large object is made harder as the digits cannot wrap around them. Again, nails were added to these digits to aid with precision tasks.

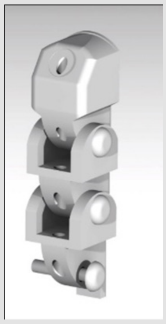


Figure 35: Index/Middle Front.

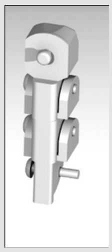


Figure 36: Index/Middle Back.

DOI: 10.26717/BJSTR.2022.46.007289

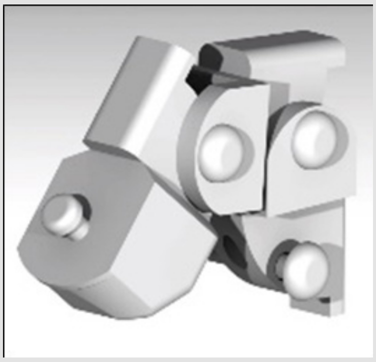


Figure 37: Index/Middle Closed.

Figure 38: Index/Middle Interaction with palm.

Figure 39: Ring/Pinkie Front.

The Combined Ring and Pinkie Finger: The combined 4th digit, otherwise known as the combined ring and pinkie finger, consist of 4 components (Figure 39). The ring and pinkie finger were combined as it simplifies the instrumentation and control element of the prosthetic. Less digits make for simpler programming and less servo/stepper motors are required. The pinkie finger is the least utilised digit of the human hand. The other digits provide all the dexterity; however, the pinkie is useful for grasping larger object. To avoid losing all the functionality of a pinkie finger, the combined ring and pinkie finger were made with a greater width than the other digits. The base component of this digit is a knuckle joint which connects to the palm of the prosthetic at an angle which allows the digit to reach across the entire hand (Figure 42). Using the same technique as in the other digits, the back of the digit uses straight components to avoid over extension (Figure 40). The 3 top components are almost identical to the index/middle finger index; however, it is double the width. These components close in the exact same fashion (Figure 41). The inward facing hinge allows the digit to contact the thumb in the centre of the hand (Figure 42). This is closer to how a real human hand works.

Figure 40: Ring/Pinkie Back.

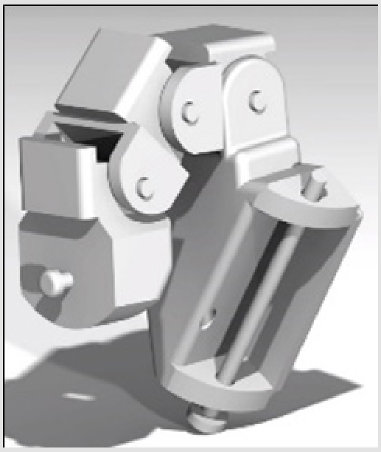


Figure 41: Ring/Pinkie Closed.

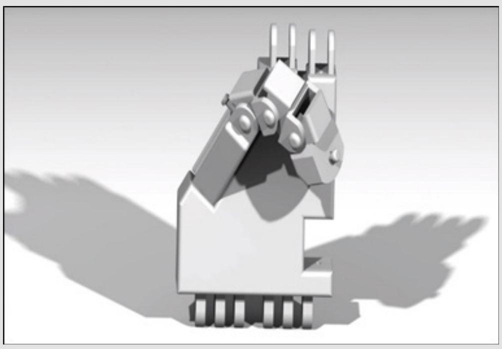


Figure 42: Ring/Pinkie interaction with palm.

DOI: 10.26717/BJSTR.2022.46.007289

Finite Element Analysis (FEA) Topology

As stated in the introduction, users of upper limb prosthetic want the prosthetic to be lightweight. The average weight of current prosthetics is roughly 460g for just the hand itself without the batteries and servo motors etc [16]. The current mass of this new whole prosthetic is 431g. This is less than average however this can be reduced further. The instrumentation for the prosthetic will be attached to the forearm component. Therefore, reducing the mass of the forearm, will result in a more even weight distribution across the arm when the motors and batteries are added. The same article claims these additional parts on average weigh 200g [16]. Reducing the mass of the prosthetic by half should result in a roughly even weight distribution.

Setting up the Model

The FEA setup was made in Hyper works. Due to the complexity of the forearm component, a 3D tetra mesh was used. Had the geometry been more simplified a mid-surface could have been made with 2D quad mesh. This would have reduced computation time and have been easier to model. The 3D mesh, although more complex to setup, models more realistic conditions and automatically considers the rigidity of the model. Figure 43 shows the model which was imported into Hyper works. The top part in red is a separate component to the forearm which was assumed to have infinite rigidity. For simplicity in the report, this will be referred to as the "FE hand". This component was included as a simplification of the hand so that the forces could be applied to it. This would then more accurately represent how the forces would interact with the forearm component. The forearm was also then split into two sperate components. The part in yellow was separated from the rest of the part as this part would be later used for the topology. The rest of the forearm in green could not have any mass removed as it was essential for the ratchet strap and hand attachments. Contact surface were created for the forearm and FE hand so that the software knew how these two components interacted (Figure 44).

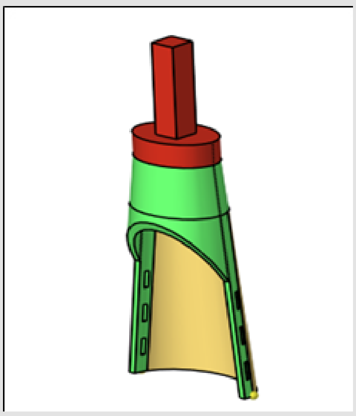
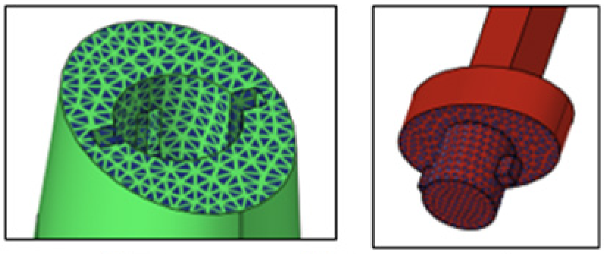


Figure 43: Model used for FEA.



Name	Value
Solver Keyword	CONTACT
Name	contact
ID	1
Color	
Include	[Master Model]
Card Image	CONTACT
User Comments	Hide In Menu/Export
Property Option	Property Type
TYPE	FREEZE
SSID	(1) contact forearm
MSID	(2) Contact hand

Figure 44: FEA Contact Surfaces.

Materials and Properties

The material properties for the forearm component were predetermined by a material study into Nylon PA12 and entered into a MAT1 material card (Figure 45). The Youngs modulus (E) was 1.215GPa, the poisons ratio (NU) was 0.414 and the density (RHO) was 1.01e3 kg/m^3. The FE hand was given a material card which assumed it was infinitely rigid. Three properties were made for each component. Each was given a PSOLID card image. Two properties were made for the forearm component so that only the section in yellow in Figure 46 would have the topology applied to. The FE hand was given a separate property as it is being assumed to be rigid. No thickness was required to be specified as a 3D mesh was to be used.

Name	Value
Solver Keyword	MAT1
Name	Nylon PA12
ID	1
Color	
Include	[Master Model]
Defined	☑
Card Image	MAT1
User Comments	Hide In Menu/Export
E	12150.0
G	
NU	0.414
RHO	1.01e-09

Figure 45: FEA Forearm Material Card.

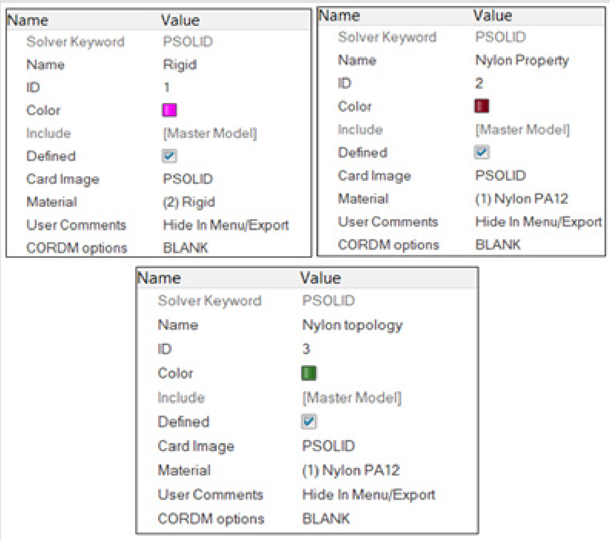


Figure 46: FEA Model Properties.

Applied Loads

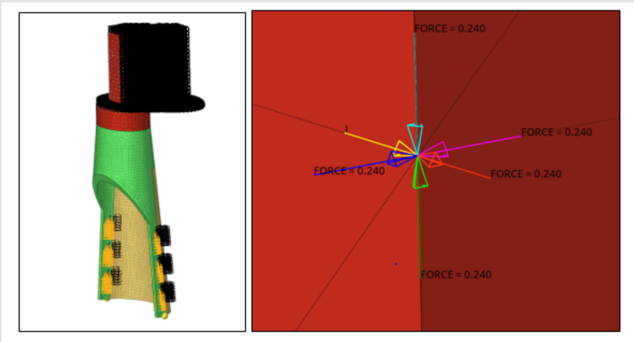


Figure 47: FEA model with Loads applied (3mm 3D tetra mesh).

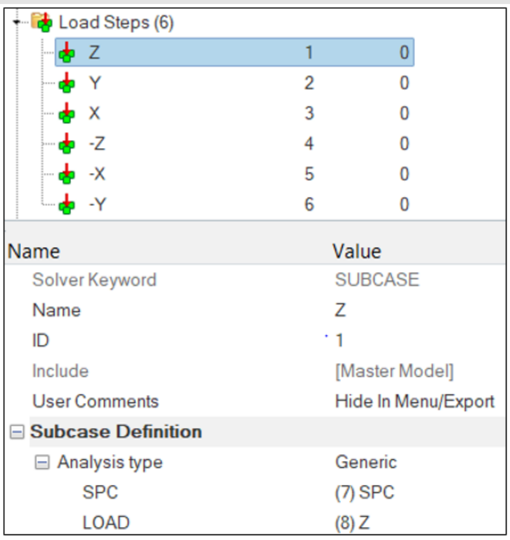


Figure 48: Example of FEA load steps.

The loads were applied to the FE Hand in the x, -x, y, -y, z and -z directions (Figure 47). The maximum lifting work safety standard for men is 25kg. This safety standard applies to lifting with 2 arms, thus the prosthetic needed to be able to hold 12.5kg. To design for robustness, this value was increased to 15kg. Thus, separate load collectors of force 147.15N were nodally distributed on the FE hand in the previously mentioned directions respectively. SPCs were applied in 3DOFs where the ratchet straps would be attached to. Separate load steps were made for each direction of loading (Figure 48).

Mesh Convergence

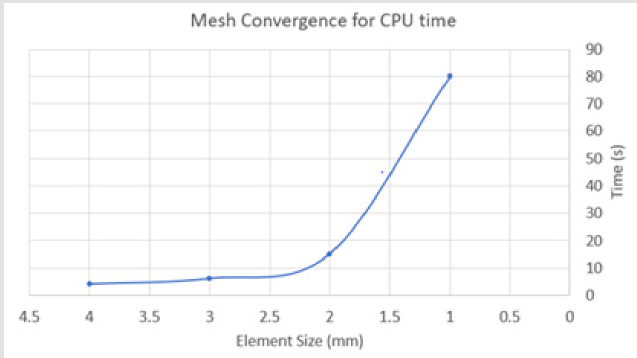


Figure 49: Mesh convergence for CPU time.

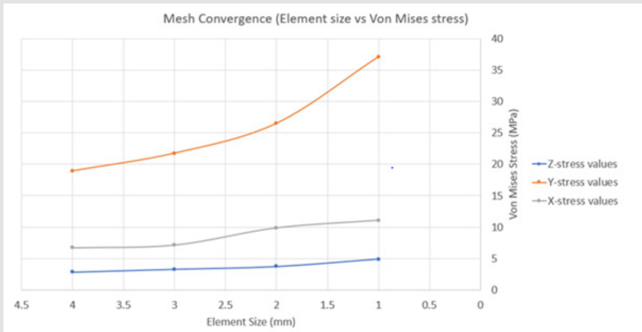


Figure 50: Mesh convergence with maximum stress values.

A mesh convergence was undertaken to choose which mesh size would be most ideal for this FEA model. Each mesh size was set up with a 3D volume tetra mesh. The graphs in Figure 49, Figure 50, and Figure 51 were used to determine wish mesh size would be the most appropriate. The mesh sizes used were 1, 2, 3 and 4mm. The first variable used in the mesh convergence was the central processing unit (CPU) run time. Figure 49 shows the CPU time with decreasing element size. Element size 4mm took 4s and element size 3mm took 6s. Both are acceptable times. The time then begins to increase more at 2mm element size (15s) and then the 1mm mesh took 79.8s. A CPU run time of over 60s will only increase when performing the optimisation stages. Thus, the 1mm element size was unacceptable. Figure 50 shows how affect element size has on the maximum Von Mises stress results. This mesh convergence shows that with smaller mesh sizes the stress values continue to rise. Between the element size 4mm and 3mm the stress values in the X and Z load case show little change. The results then increased in all three cases. The X-stress values showed some convergence between 2mm and 1mm suggesting there may be convergence at smaller element sizes, however the CPU time would continue to increase.

Figure 51 shows the maximum displacement values with decreasing element size. For the Y-load case, the values appear to converge slightly between 3mm and 2mm but then continue to increase linearly. Whereas for the other two load cases the displacement values remained consistent, with only minor linear increases. For an accurate study in FEA, when using 3D meshing, a minimum of 3 elements spanning the width is required. The 4mm mesh was too large to achieve this, which left the 2mm and 3mm element sizes to choose from. The 3mm element size was chosen as it had a lower CPU run time while sharing many similarities in results to the 2mm mesh size. In addition, the change in results between the 4mm and 3mm mesh size were the smallest. Figure 52 shows the model with a 3mm mesh.

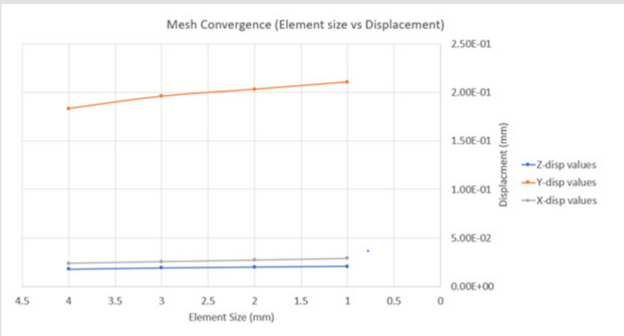


Figure 51: Mesh convergence with maximum displacement values.

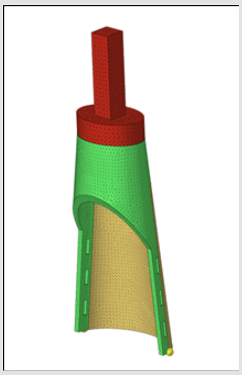


Figure 52: FEA model with 3mm mesh.

Topology

These results were used for the next stage. The next stage of the FEA was to perform the topology optimisation and compare these results with the results of the original structure. The aim of the topology was to reduce the amount of material used in the forearm component, thus reducing the mass of the prosthetic. The topology would do this without compromising the strength. The first step of the topology was to create the design variable. The yellow section (Nylon topology) of the model was chosen as the design variable property stating the model was a P Solid. The objective of the topology was set to minimise mass and a constraint of static stress was applied to the whole forearm component with an upper bound of 20MPa was set. This was to ensure that the topology results would not exceed the yield stress of Nylon PA-12 (35MPa). The topology was then set with a pattern group of cyclic with 1 plane of symmetry. The results of this can be seen in Figure 53.

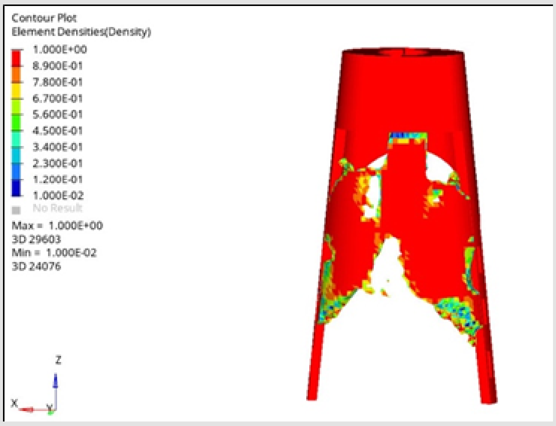


Figure 53: Element Densities of Topology.

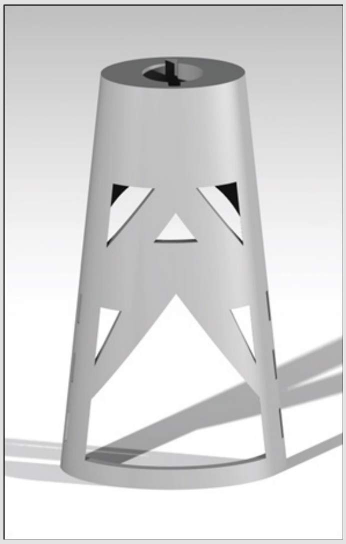


Figure 54: Forearm Component with Topology.

The resulting topology showed that lattice structure formed between the two columns running down the length of the forearm where the ratchet straps would be attached to. The element densities shows that the lower end of the forearm component is

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not required, however some structure was included in the final design so that there were not two columns sticking out which could be unsafe. Most of the material is required in the middle of the forearm component. This topology was used for the design of the new Forearm component (Figure 54).

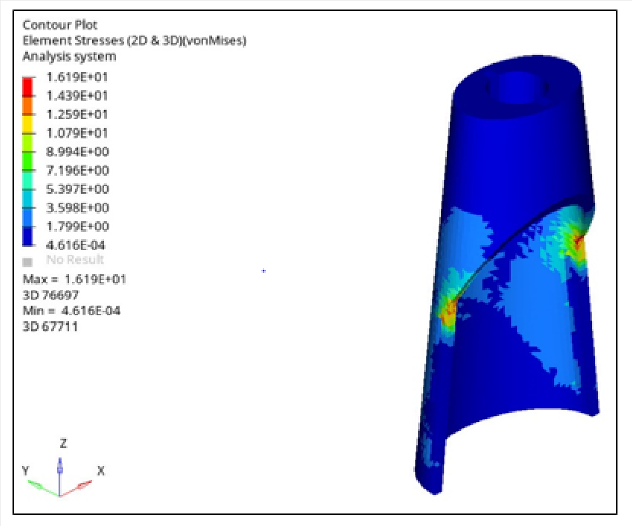

Figure 55: Von Mises Stress Results Before Topology (MPa).

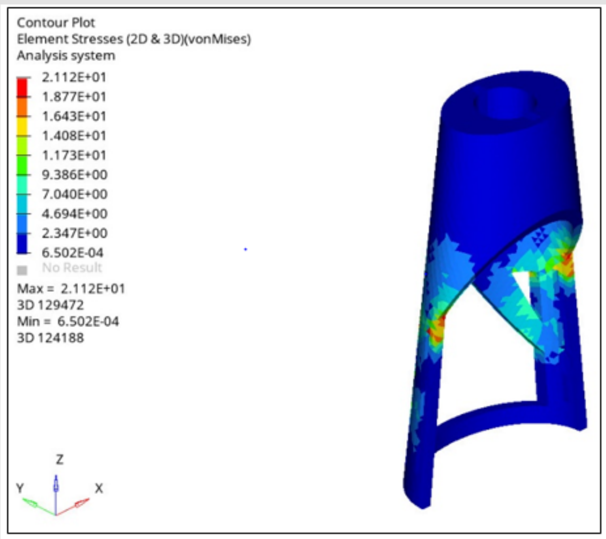

Figure 56: Von Mises Stress Results after Topology (MPa).

The initial mass of the forearm component was 205.2g. The mass of this component was required to reduce mass as to be more comfortable for the consumer and once the instrumentation is introduced the prosthetic will have an equal weight distribution across the whole prosthetic. After the topology optimisation the mass of the forearm component was reduced to 171.5g. The new topology version of the forearm component was set up in FEA under the same conditions as the original model. Von Mises was used as it is the summation of stress at each point on the model, ideal for determining if a material will yield. The highest Von Mises Stress values were found when the forces were applied in the Y-direction before (Figure 55) and after (Figure 56) topology. Before topology the highest Von Mises stress was 16.19MPa and after topology it was 21.12MPa. These values are concentrated at the corner where the half cone shape becomes a full cone shape. This could be reduced by increasing the angle where this concentration is located. Nevertheless, the yield stress of Nylon PA-12 is 35MPa, thus the material does not yield. The areas of high stress concentration are still points in the design to consider as if the component does fail it will be at these points. The displacement values before (Figure 57) and after (Figure 58) topology is low. Before topology the maximum displacement was 0.25mm and after topology it was 0.42mm. These values are in the same area at the top of the forearm component because the forces are applied at this end of the component. The displacement in the topology component is acceptable and will not be noticeable to the consumer.

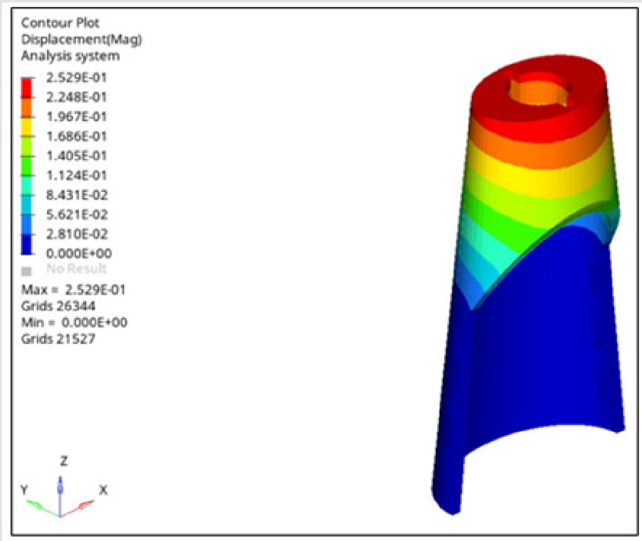

Figure 57: Displacement Results before Topology (mm).

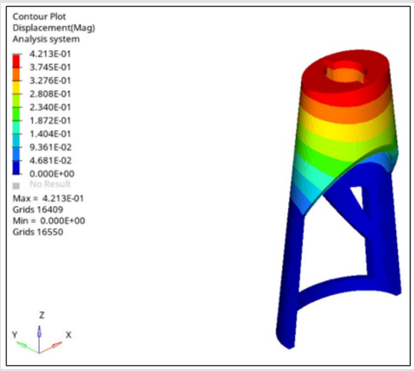

Figure 58: Displacement Results after Topology (mm).

The Final Design

The new forearm component with topology was added to the

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final design (Figures 59 & 60). The overall mass of the prosthetic was reduced from 431g to 248g; a reduction of 42.46%. This is lower than the average of roughy 460g [15]. These mass values only apply to the mass of the material for the prosthetic. The instrumentation and control are beyond the scope of this project. The mass values were calculated in Hyper works; this assumes that the prosthetic material is solid throughout. However, 3D printing uses a lattice internal structure which means that the true mass of the prosthetic would be less. Furthermore, the stress and displacement values simulated would also slightly differ.

Figure 59: Final Design Front.

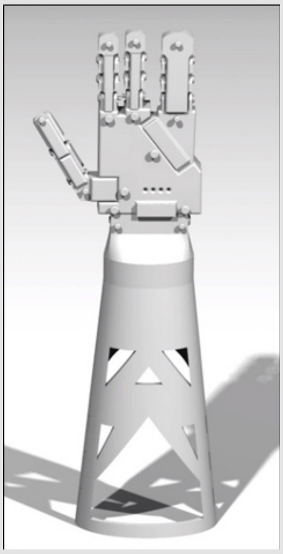

Figure 60: Final Design Back.

Prototyping

The prototype was made prior to the topology; thus, the forearm component is made from the original design. The prototype was made to test whether the parts were possible to 3D print and whether the hand was capable of all the movements required by it. Nylon PA-12 was not available for the university 3D printer and so PLA was used instead. The prototype was not printed perfectly which resulted in some rough edges, the fingernails did not print effectively because of this. Nevertheless, the general shape and functionality was successful (Figure 61). The prototype did not include the instrumentation or control, however the rubber bands and 0.4mm nylon wire were included to test if it was functional. Washers and a handle were attached to the ends of the nylon wires so that the prosthetic could be controlled like a puppet. Each digit could be controlled independently by pulling the different washers and they could be controlled together using the handle. This meant that the different grips could be tested. The following figures show an example of the grasps the prototype could successfully perform. The tips of latex rubber gloves were put onto the prototype to give the extra friction required to pick up objects. The types of grips were based on the Cutkosky taxonomy tree.

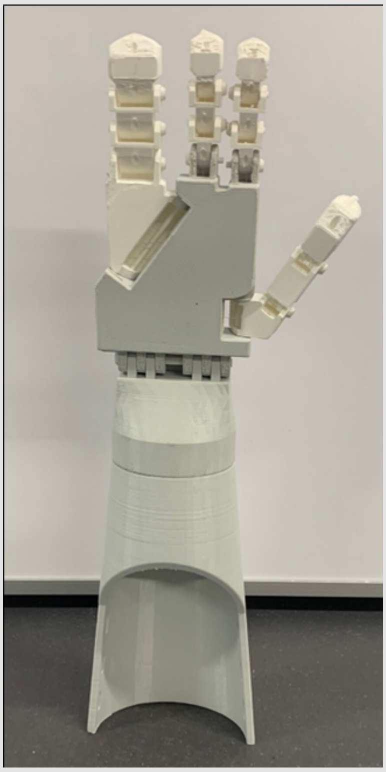

Figure 61: Prototype.

Validation

Being able to use cutlery was common consumer requirement found in the literature. Figure 62 shows a lateral pinch grip to pick up a fork. Figure 63 shows a close up of the prototype performing a thumb-index finger grasp. Figure 64 shows the prototype performing a Thumb-2 finger grasp and Figure 65 shows it

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performing a medium wrap grasp. The prototype could perform these actions, however grasping larger objects was challenging. The movement of the digits works as planned, however having larger digits would allow for bigger objects to be held. This would also allow for a greater grip strength as the digits could press harder against the thumb. Furthermore, it would be advantageous to control thumb in two ways. One control to move the opposition of the thumb and one control to operate the open and closing. This way the thumb could contact all the digits. Currently, the thumb bends too much to contact the ring/pinkie finger.

Figure 62: Prototype picking up fork (lateral pinch).

Figure 63: Prototype Thumb-index finger grasp.

Figure 64: Prototype Thumb 2 finger grasp.

Figure 65: Prototype Medium Wrap Grasp.

Price					
Price	ⓘ	* 4.78	-	6.62	GBP/kg
Price per unit volume	ⓘ	* 4.78e3	-	6.76e3	GBP/m^3

Figure 66: Nylon PA12 Costings [41].

Other areas of the design which need editing would be the size of the pins for the rubber bands. These were only given a diameter of 3mm. During post processing of the 3D printed parts, the leftover plastic support structures needed removing. During this removal process, 2 two of the pins snapped off and needed to be attached back on with adhesive. Furthermore, the nylon wires were attached using epoxy resin and cement. The original plan was to tie this wire onto a bar that would be located at the top of the threading hole in each digit tip. This was not possible as the threading hole diameter was too small, and the support material would have been irremovable. Finally, the thickness of the palm cover could be reduced. This would be beneficial when making the prosthetic doing a heavy wrap. The current thickness protrudes past the plane of the digits. This means the digits must reach out further to grasp objects.

Costings

The main costing for the consumer will come from material costings. Granta Edupack states that the average cost of Nylon PA12 per kg is 5.70GBP/kg (Figure 66). The prosthetic will use 0.248kg of material making the material cost £1.41 for each prosthetic. Of course, for different people the price will change as they will have different sized forearms. The larger forearms will need more material which will increase the price. The Ultimaker 2 3D printer used in the EEC university workshop has a power output of 221W. The print time for the prosthetic was 30 hours. Therefore, the 3D printer will be using 6.63kWh. Energy prices around the world vary, but in the UK, at the time of writing, the average energy price was 18.9p/kWh. Energy prices will increase in future. The overall cost of the average energy consumption for manufacturing the prosthetic will be £1.25 (based on current prices). Labour costs are more complex to determine. Factors that come into effect are post processing, setting up the print and supervising the print. Based on the minimum wage in the UK being £9.50, the labour costs for the printing process will be £285.

This makes the overall cost of the product £287.66. Usually, if a separate business is manufacturing the product, they include a 10% markup cost. This would result in the final price for the consumer to be £316.43 plus the cost of the servomotors, battery, and myoelectric kit. The control and instrumentation of the prosthetic is for future work, thus the cost of this will need to be calculated later. The overall price calculated will vary depending on which 3D printer is used. A faster printer will reduce the run time but will cost more to operate. On top of this, if this project is taken on by a charity or the UN, they may invest in 3D printer to manufacture themselves. Continuing with the Ultimaker 2 example, to purchase this will cost £2,135 from RS components [42,43].

Conclusion

Future Works

The prosthetic has been designed up to the point where each digit is controllable by pulling on individual nylon wires. The instrumentation and control such as the myoelectric kit, servo/stepper motors and batteries are the next big stage of the project. The myoelectric sensors will detect muscle stimulation and activate the servo/stepper motors which will pull on these nylon wires, controlling the fingers. The same needs to be applied for the wrist movement. The wrist currently does not have the nylon wires considered in the design, so this is also a plan for further works. Furthermore, the inside of the forearm component needs to be made more comfortable for the consumer. This can be done by lining the inside with a soft fabric and using memory foam to form around the shape of the stump. This is important as no amputee has the same shape of stump. Amputation caused by trauma can be any shape of size. A combination to include nitrile within the forearm component as well may improve the purchase on the arm.

The fingers of the prosthetic need to be increased in size so that it easier to grasp larger objects. This is a simple fix by increasing a few dimensions within the CAD model. Furthermore, the entire prosthetic could be analysed using FEA to properly stress test the hand. This will determine whether certain components need further strengthening. The prototype felt strong when using it, however there was some movement laterally. The finish and strength of the prosthetic can be improved by a composite 3D printer and using a layer of elastic resin on the outside of the prosthetic. This will also improve the grip. Another further development is to add a thread to the pins so that they be attached using a nut. This will make maintenance easier as all the parts can be separated and replaced individually. This will reduce repair costs for the consumer as if a part got damaged, such as a fingertip, they need only reprint that one component.

Final Remarks

The purpose of this project was to design a functionally effective upper limb prosthetic which could be distributed affordably in developing countries. This project has concluded with a design which has a high range of motion, is lightweight, adjustable and can be manufactured affordably using 3D printing. It also allows for easy maintenance with room for modifications to be made to individual components. All the objectives in this project were met. The final design and prototype confirm the hypothesis of this project. By designing for 3D printing, with the use of topology optimisation, a lightweight functional prosthetic was produced. The prosthetic provides the necessary range of motion to interact with the environment and grasp object such as cutlery. By using 3D printing technology, complex shapes can be manufactured with ease. This meant that a topology optimisation could be performed on the prosthetic which reduced the weight by 42.46% resulting in a mass of 248g. This mass is lower than the 460g average for the mass of material in other myoelectric prosthetics.

The cost of the prosthetic is low, the overall cost calculated was £316.43, this includes labour cost (assuming minimum wage). This does not include the instrumentation and control, but this value is a lot less than what is currently available on the market. The main competitor to this would be the Flexy Hand 2 (Figure 12) (£50), however the price of this does not include the labour costs which would increase the price above what has been produced in this project. Producing the prototype showed that all the parts successfully printed, despite some errors during the print which were possibly caused by someone knocking the machine. The prototype proved that the hand was capable of dextrous tasks and could handle a range of grasping motions. IT had a strong grip strength which will be better controlled once the instrumentation has been implemented.

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