Mechanical Design and Development of the Touch Hand II Prosthetic Hand

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The Touch Hand II is a desktop 3D printed prosthetic hand that has been developed to improve on the first design iteration, in order to reach the goal of providing transradial amputees with a low-cost alternative prosthetic hand, in comparison to commercial options. The powered grip strength, closing/opening times, mass, power usage, aesthetics, structural integrity, and cost have all been improved on through this research. The new design is compared to five other low-cost hands and two commercial hands. This comparison shows that the new design has seven characteristics that are similar to or outperform the commercial products. The same can only be said for at most four characteristics of the other low-cost hands. This paper focuses on the mechanical design of the major hand components, although it is also shown how the custom circuit board fits in the palm, and an overview of the programmed control system is described, with possible future additions of amputee feedback and command input.

Additional keywords: Prosthetic hand, low-cost, development, comparison to commercial options.

Nomenclature

Roman

T torque [Nm]
W weight [kg]

Subscripts

MCP at metacarpal-phalangeal joint
h static hook load

1 Introduction

It has been recorded that approximately over 1,564,000 individuals in the USA have amputations, of which 900,000 have their fingers/toes or a hand amputated [1]. This would obviously be a larger number if the rest of the world was considered. For these amputees, it would be ideal to be able to replace their lost limbs with technology that could replicate their previous functionality and aesthetics.

Major advancements have been made with prosthetic technology since World War II, when body-powered prostheses were more commonly used [2], including more realistic and functional innovations; which include a number of designs in the research and commercial sectors. The research-based Southampton-Remedi hand is an early example of a five finger, or digit, light-weight design with multiple degrees-of-freedom (DOFs) and individual digit actuation, with the actuators embedded in the palm [2]. A recent commercial hand is the i-limb Ultra Revolution, by Touch Bionics, which is more complete, having up to 24 selectable grip patterns, user training support, and cell phone application control and configuration [3].

Commercial hands are commonly interfaced with the user by non-invasive electromyography (EMG) technology; which measures muscle contractions with the myoelectric signals (MES). The most prominent MES measurements are determined by placing electrodes at specific positions on the skin, over the targeted muscles [4]. The mean absolute values (MAV) of MESs have been used to proportionally control a motion parameter of the hand, such as speed or torque. Alternatively, the MAVs have been compared to defined thresholds to detect active states, which can then turn on or off a set motion parameter [5].

A current problem with the most advanced commercially available prosthetic hands, such as the i-limb Ultra, bebionic, and Michelangelo, is cost, which ranges approximately between US$ 35,000 and US$ 75,000 [6]. These high costs motivated the work done for the Touch Hand I. The Touch Hand I is a proof of concept prosthetic hand with a low cost mechanical and electronic design, controlled by a user via a surface electromyography (sEMG) based interface and control system. Additionally, grip force and temperature sensory feedback is given to the user through vibrating motors. The hand can be set to more than 14 different grips and gestures (19 were tested), and it can be constructed with materials costing less than US$ 1000 [7].

When budget is not a concern, highly complex and functional prosthetic hand and arm projects are achievable, such as the Modular Prosthetic Limb (MPL) [8], and the DEKA Arm [9]. Although, higher budget projects do not always produce practical prosthetic hands, such as the DEXMART Hand [10], which uses tendons and actuators placed within the forearm, doing so eliminates the use of the hand by users with amputations closer to the wrist. Comparatively, there are a number of identified problems with low-cost prosthetic hands. These issues resulted from analysing the characteristics of five low-cost [7], [11]-[14] and two commercial hands [3], [15], which related to functional performance, aesthetics, structural integrity, and fitment limitations. A summary of these characteristics was made and is provided for discussion purposes later in section 10. More specifically, the characteristics of the low-cost hands, which either out-perform, or are similar to the commercial options are closing/opening time, number of actuators, mass, maximum power usage, aesthetics, and fitment limitations. Most importantly, not one of the evaluated low-cost options has more than four out of ten characteristics that are similar to, or exceed, one of the commercial options.

This paper describes the mechanical design of the Touch Hand II prosthetic hand, which is an overall improvement over the previous version and other low cost solutions in

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terms of the considered characteristics. The Touch Hand II has seven out of ten characteristics that are similar to or outperform two commercial products. Contributions include the design of alternative finger drive mechanisms, the palm for improved strength and motor placement, and the overall mechanical integration with the electronics.

2 Design Considerations

A number of design aspects were considered in great detail to understand all the options that could contribute to improving the design of the Touch Hand I. These were the aesthetics, mechanisms used for the fingers, the methods of actuation, and materials.

2.1 Aesthetics

The aesthetics of the hand determine how natural it looks when attached to an amputee. There were three important aspects that were addressed under this topic: the DOFs, the form factor, and limitations on the type of amputations necessary to attach the hand.

The human hand naturally has over 23 DOFs, but advanced prosthetic hands in literature commonly have between 8 and 16 DOFs [14]. This difference in DOFs proves the difficulty of replicating all the DOFs of a natural hand. 14 DOFs were chosen for the Touch Hand II, which provide suitable functionality without unnecessary design complexity. Multiple DOFs do not create natural aesthetics without considering the form-factor. In order to accommodate most amputees with a proportionally sized hand with one design, anthropometric data from the ANSUR database was used as a reference [16]. Initial concept dimensions were based on 50^{th} percentile data. A natural looking hand is not useful to an amputee if they are amputated at the wrist, but the hand design extends into the wrist without any adjustment. The hand was designed with intrinsic actuation, allowing amputees to attach it from the wrist.

2.2 Finger Joint Mechanisms

Not all of the joints of prosthetic hands in literature are independently actuated; commonly, up to 6 actuators can be found in prosthetic hand designs. These hand designs have more degrees of freedom (DOF) than the number of independently driven joints, or degrees of motion (DOM), due to using underactuated finger drive mechanisms. Common methods of underactuation include: differential systems, compliance couplings, kinematic linkages, or a combination of these [14]. A differential system has been used to simultaneously actuate multiple fingers [17]. Alternatively, joint compliance enables joint positions to change relative to one another with an external load, without a change in the driving joint position. This has given mechanical fingers the ability to adaptively wrap around the surface of objects, distributing surface forces more evenly along the finger. Compliance couplings generally use springs, which apply mechanical load on the actuator during finger flexion and/or extension - wasting energy. As another option, the relative rotational motion between each of the joints can be predetermined using a design of kinematic linkages [14]. A kinematic linkage based design was created because of its simplistic mechanics and ease of control, due to the defined motion relationship between each joint. Furthermore, it conserves energy because no springs are present. This design is described in more detail in section 3.

2.3 Actuation

Selecting a specific actuation technology can change the design on the hand entirely. Actuation and power generation components affect size, cost, and complexity requirements. Most prosthetic hand designs attempt to fit actuation systems within the palm of the hand. This accommodates transradial amputees up to the wrist. Five technologies found in literature were considered: motors [18], body power [19], hydraulic [20], pneumatic [21], and shape memory alloys (SMAs) [22]. Despite the disadvantages of brushed DC motors (limited speed and generated electromagnetic interference due to the brushes), the low cost, high power to weight ratio, wide variety, availability, easy control, and simple selection made them the actuator of choice over other options. Moreover, DC motors are the most common form of actuation in previous prosthetic hand designs [18]. Six motors are used, two for the thumb and four for the other fingers, each driving a single joint. The index, middle, ring, and small fingers each have one driving motor to control them individually, enabling more realistic hand motion control for a large number of grasps and gestures.

2.4 Materials

The combination of materials used in prosthetic limbs need to balance cost, manufacturability, mechanical performance, and weight. There are a variety of traditional (metals) and modern materials - polymer matrix composites (PMCs) and plastics - being used in prosthetics. Various materials used in prosthetic hand designs were identified in research, listed in table 1, to provide guidance for the material selection process.

Table 1 Major Materials in Prosthetics in Literature.

Material Type	Material Name	Reference
Metal	Aluminium	[23], [24]
Metal	Titanium	[25]
PMC	Carbon Fibre	[26], [27]
Thermoplastic	un-named	[14], [27]
Thermoplastic	ABS	[28], [29]

Although thermoplastics do not have similar mechanical performance characteristics as Aluminium, Titanium, or PMCs, specific types can be used with new desktop 3D printing technology, using fused deposition modelling (FDM), at relatively low costs. Not only can parts be printed out in a few minutes, there are little limitations on the shapes in comparison to other materials, and they are lighter in weight. For these benefits, acrylonitrile butadiene styrene (ABS) thermoplastic was selected as the primary material. Printing was done using an UP! 3D printer with a 0.4 mm nozzle diameter and a 0.15 mm printing resolution for fine details.

3 Palm & Fingers

The same actuation mechanism was used for the small, ring, middle, and index fingers. These fingers each have three main bones and joints: the metacarpal-phalangeal (MCP) joint is commonly known as the knuckle, followed by the proximal-interphalangeal (PIP), and distal-interphalangeal (DIP) joints.

Starting from the MCP joint, the bones are the proximal, middle, and distal phalanx/phalange. Six identical motor and gearbox combinations (Faulhaber 1717_SR motor and 15A 152:1 gearbox) were used to independently actuate each of the MCP joints of the index, middle, ring, and small fingers, as well as the carpometacarpal (CMC) and DIP joints of the thumb.

The arrangement of the fingers on the palm, except the thumb, is shown in figure 1. The MCP joints of the fingers share the same rod to simplify the palm design. These fingers all have the same finger actuation mechanism to minimise complexity, reduce manufacturing time and costs. The palm holds five of the six motors, but has a shape that maintains rigidity and a natural aesthetic appeal. Its unique design is inspired by the arrangement of metacarpal bones that sit in the palm of a human hand. Where these bones would be in the prosthetic hand are bone-like structures that strengthen the design by increasing the second moment of area. This moment of area is applicable to the plane perpendicular to the palm and through the MCP joints. Specifically, these structures sit in between the actuators of the index to small fingers in figure 1.

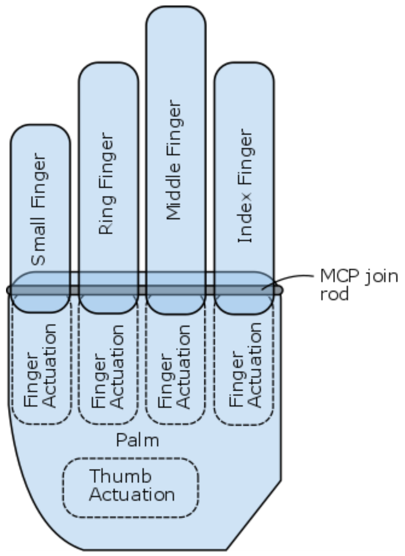

Figure 1 Straight Palm Concept.

A novel underactuated finger mechanism was designed, shown in figure 2, based on cables arranged in a way that all the joints were mechanically linked. These cables linked the relative motion of the joints together. This is similar to traditional linkage designs, except that traditional designs use bars instead of cables. As a result, the mass is reduced and the relative motion between each joint is linear. This design's natural joint position control, high energy conservation, low cost, and reduced design effort made it more appealing than other considered concepts.

The principle operation is based on cables a, b, c, and d, which are attached to specific pulleys 1, 2, 3, and 4 at each of the joints; MCP, PIP, and DIP. Pulley 1 is fixed to the palm, pulley 2 is fixed to the proximal phalanx, pulley 3 is fixed to the middle phalanx, and pulley 4 is fixed to the distal phalanx. Cables a and b are connected to pulleys 1 and 3, and cables c and d are connected to pulleys 2 and 4. When a torque is applied on the proximal phalanx at the MCP joint, the proximal phalanx will rotate about the joint, while the PIP and DIP joints rotate relatively by a defined ratio with respect to one another. This ratio is determined by the pulley diameters.

The relationship of relative motion and torques between joints are simplified by using the pulley ratios, allowing simplified kinematic design. Cables are lighter in weight in comparison to bars in linkage designs and take up less space. On the contrary, four cables and eight connection points make the design intricate to assemble.

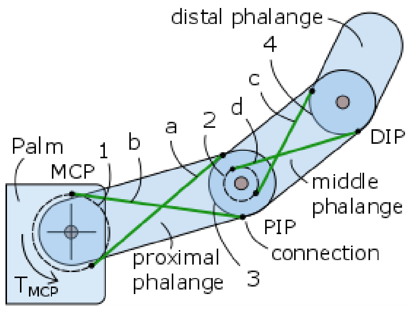

Figure 2 Cable Linkage Concept.

Figure 3 shows how actuation is coupled between the motor shaft and the MCP joint, using cables and pulleys. Pulley 1 is passive and pulley 2 is fixed to the proximal phalanx at the MCP joint. A cable is fixed and wrapped around the motor pulley, fed over pulley 1, wrapped around and attached to pulley 2 before following a similar path back to the motor pulley. The speed ratio is dependent on the diameters of the motor and MCP pulleys.

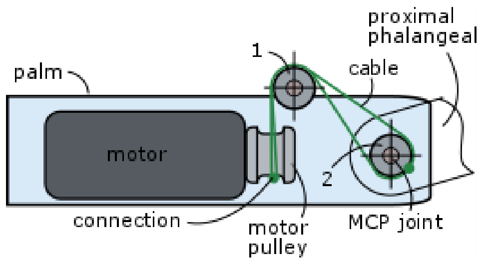

Figure 3 Pulley Finger Mechanism Concept.

One major design advantage over other considered concepts was the optimised usage of space. Additionally, the motor axis is in line with the MCP joint, minimising the thickness of the palm. One disadvantage of this design is that it is not self-locking, as with worm-gear drives.

4 Thumb

Re-creating the DOFs of the thumb is extremely challenging, and so the problem was simplified by reducing the degrees-of-freedom to two. The CMC and MCP joints were selected as being most important. Cables, pulleys, and motors were again used to actuate these joints in order to minimise space usage.

Figure 4 illustrates the set up for the CMC joint, looking down on the palm. The rotational axis was tilted toward the centre of the palm to achieve more natural finger positions during motion. A motor drives a cables via an attached pulley. The cable then moves along a separate passive pulley, before moving around the diameter of the CMC joint, and back on a similar path to the motor pulley. Again, a disadvantage of this mechanism is that it is not self-locking.

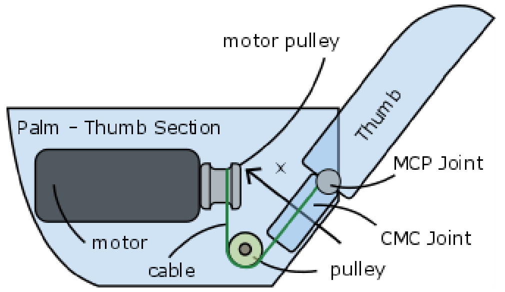

Figure 4 Thumb Pulley CMC Joint.

The MCP joint was actuated by a motor placed within the thumb, as shown in the sectioned 3D design of figure 5. The motor drives the pulley, with a cable wrapped around and attached. The cable is also attached to a pulley fixed to the MCP joint. When the motor turns, one side of the cable wraps around the pulley, while the other side unwraps. The same can be said for the cable wrapped around the MCP joint.

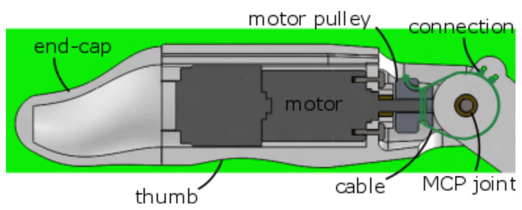

Figure 5 Thumb Pulley MCP Joint (Cross-Section).

5 Design for Assembly

Once the dimensions of the design were finalised, parts were printed and assembled together to physically verify the operation of the fingers and the types of fits. Furthermore, the placement of a custom electronic board within the hand was considered, as well as the design of a temporary wrist for the sole purpose of attachment to a specific custom socket of an amputee. This socket was made for basic amputee testing and demonstration purposes of the first iteration of the hand, the Touch Hand I, and has been incorporated for similar basic tests.

Although the design was based on a left hand model, a right-hand version, shown in figure 6, was made by printing out the mirrored parts. In some cases, part dimensions had to change to acquire the correct fits because the orientation of the parts during 3D printing would affect the dimensional resolution. The printer's horizontal layer resolution was better than the vertical resolution. Where necessary, part dimensions were filed down to achieve tighter tolerances.

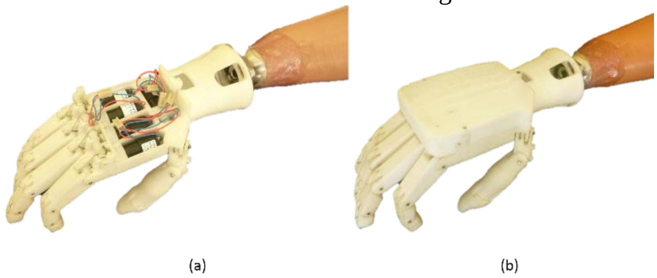

Figure 6 Constructed Hand: (a) without top cover or electronics, (b) with top cover.

A custom electronic board was designed and manufactured to support the control of the hand. Figure 7 shows the board placed in the hand with the cover removed. The hand was designed such that the left and right hand version would accept the same printed circuit board (PCB) design, saving manufacturing costs and design time. To optimise space usage, all the surface mount components were placed on one side, while all discrete components were placed on the other. For the left-hand version, the PCB is flipped over. Neither figure 6 nor figure 7 show the power cable that can be plugged into the electronics near the base of the thumb. The other end of the cable can be connected to a variable power supply for testing purposes, or a battery pack to be placed in a socket. The socket used here did not accommodate space for a battery pack.

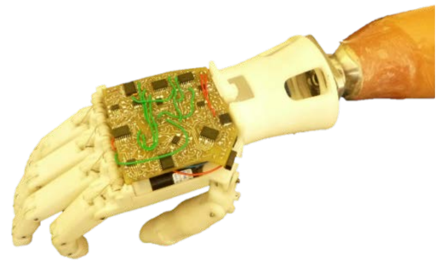

Figure 7 Physical Right Hand with Electronics.

The attached wrist and socket are clearly seen in the previous two images of figure 6 and 7. The steel interface of the socket is commonly used by prosthetists for hook designs. The plastic wrist has spaces in the design for bolt access; four bolts for the socket interface and three screws to fix the hand to the wrist. Moreover, the wrist allows a 90º rotation between itself and the socket before tightening for slight adjustments. This temporary design was used to create a foundation for testing with a specific amputee.

6 Control

A brief overview of the control strategy is provided to enable an understanding of the hand holistically. To give the hand functionality, each of the fingers were controlled by their position, speed, and grip force. Control software was designed and programmed onto a microcontroller (MCU) to achieve this. Figure 8 shows the command and feedback flow paths within and between the electronic sub-systems, with commands by an amputee being replaced by a computer (PC). The embedded sub-system is contained within the hand, while the external sub-system is directly involved with amputee communication. The scope of this research did not include implementing a software and electronic interface between the amputee and the hand.

A custom graphical user interface (GUI) was created in Visual Studio, using Visual Basic code, to simulate the commands from the amputee. Different levels of torque, speed, and position settings were available. Torque and speed control were based on a proportional integral (PI) controller. The closing and opening sequence of each finger was achieved with a finite state machine (FSM).

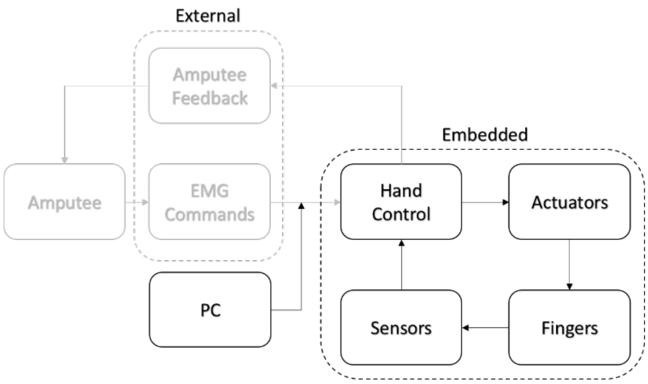

Figure 8 Overview of Hand Control via the PC.

7 Kinematics

Kinematic models of the fingers and thumb were derived to generate motion analyses and allow future model comparisons. The Denavit-Hartenberg (DH) notation was used to determine the joint and link parameters, which then led to the determination of the DH transformation matrices, one for each link. These matrices were used to determine the position of each link in 3D space for specific joint angles.

Motion profiles were produced for the fingers and the thumb by plotting link positions for corresponding joint angles. For the fingers, the first joint angle was incremented between the full range of motion, from 0° to 110°. The second and third joint angles depended directly on the first joint angle due to the cable linkage design.

The graph of figure 9 shows a 2-D plot of each finger motion for the changing first joint angle. An angle difference of 2° was used between the first joint angle of each finger, to avoid overlapping. The small and middle fingers are represented by black and red, respectively. The ring and index fingers are represented by blue because they have the same dimensions.

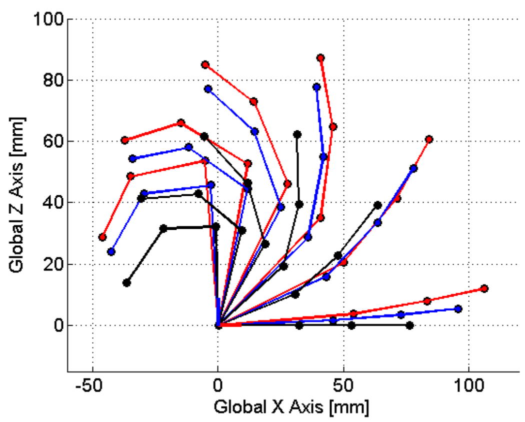

Figure 9 2-D Fingers Kinematic Motion Profiles.

For the thumb, the first joint angle and the second joint angle are independent. These angles were incremented throughout their range of motion, 0° to 90°. This is best represented visually in 3D, as shown in figure 10. For each incremented CMC joint angle, the MCP joint angle was incremented throughout its motion range. Each colour represents a different CMC joint angle.

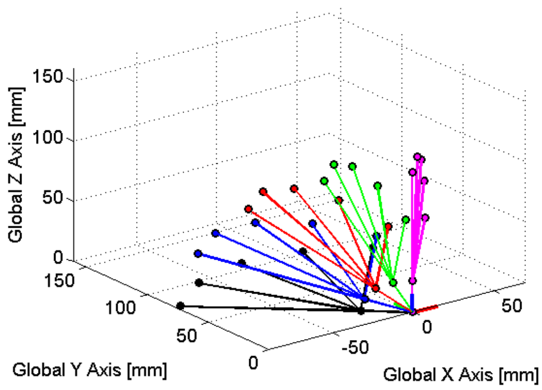

Figure 10 3D Thumb Kinematic Motion Profile.

8 Stress Failure Design

A finite element analysis (FEA) was done on the most critical parts to check for possible load failures. The design was adjusted to be able to handle the estimated maximum loads. The worst case loading conditions were considered with a total static hook weight load, W_h, of 112.8 N. Solidworks SimulationXpress was used to produce analysis results in a short time frame by assuming a linear static scenario; the assumptions are that the model responds linearly to the load, the material is loaded in its elastic range, and the loads are static. The mesh consisted of tetrahedral shaped elements ranging in size from 0.1 mm to 1 mm. The material properties used were those present in the Solidworks' material library, as listed in table 2, except for the yield strength. The ultimate tensile strength of ABS is given as 30 MPa in the Solidworks' library, but a plastic manufacturer published the tensile yield strength to be 42 MPa [30]. The tensile yield strength should be less than the ultimate tensile strength, but these data contradict this statement. Thus, to be conservative, the lower value of 30 MPa was taken as the yield strength. In the simulations, applied loads are represented by pink arrows, and fixed points are represented by green arrows. Safety factors of at least 1.5 were accepted.

Table 2 Material Properties of ABS used in FEA

Property	Value
Elastic Modulus [GPa]	2
Poisson's Ratio	0,394
Shear Modulus [MPa]	318,9
Mass Density [kg/m^3]	1020
Ultimate Tensile Strength [MPa]	30
Tensile Yield Strength [MPa]	30

For the FEA on the bottom part of the palm, shown in figure 11, the wrist face was assumed to be fixed, while the load W_h was evenly distributed between each MCP joint connection point. A maximum stress of 17.5 MPa was computed, giving a 1.7 safety factor.

Figure 12 shows the FEA of the middle finger proximal phalanx. It was assumed the worst case condition would be the load $W_h/4$ distributed across the indicated face. A maximum stress of 6.41 MPa gave a safety factor of 4.68.

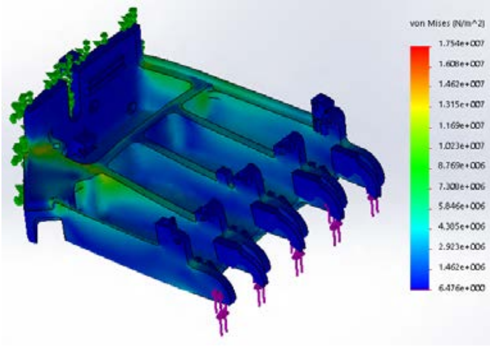

Figure 11 Finite Element Analysis of Palm.

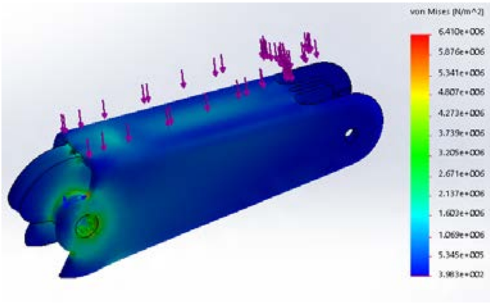

Figure 12 Finite Element Analysis of the Middle Finger Proximal Phalanx.

The middle and distal phalanxes do not experience any direct load in the considered load case. They were assumed to have a maximum load of 49.0 N (5 kg). This was applied at the DIP joint for the middle phalanx, shown in figure 13, and on the indicated face of the distal phalanx in figure 14. Stresses of 19.3 MPa and 9.67 MPa were computed for the middle and distal phalanxes, corresponding to safety factors equal to 1.55 and 3.1, respectively.

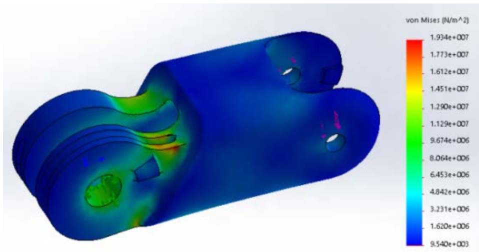

Figure 13 Finite Element Analysis of the Middle Finger Middle Phalanx.

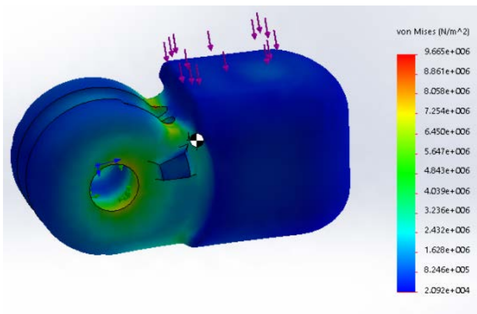

Figure 14 Finite Element Analysis of the Distal Phalanx.

9 Results

We have performed a number of tests to measure the characteristics of the hand in order to evaluate it holistically against other low-cost and commercial alternatives. The first tests relate to grasping abilities and grip strength, followed by closing times, mass, aesthetics, power consumption and attachment limitations.

9.1 Dexterity

The dexterity represents how well the hand can move its fingers into positions such that various grasps can be achieved. The ten most frequently used grasps were used as a baseline for the taxonomy [31]. These consisted of 80 % of the observed grasps. The ten grasps and corresponding attempts by the hand are shown in figure 15; the hand grasp symbols were extracted from [31]. The hand did not have a glove or any material placed onto it for grip testing, and so the plastic was the only surface available. The low friction coefficient of the plastic did not allow objects to be held in a fixed position well, but it was planned that material could be placed on the finger in the future to improve the grip ability.

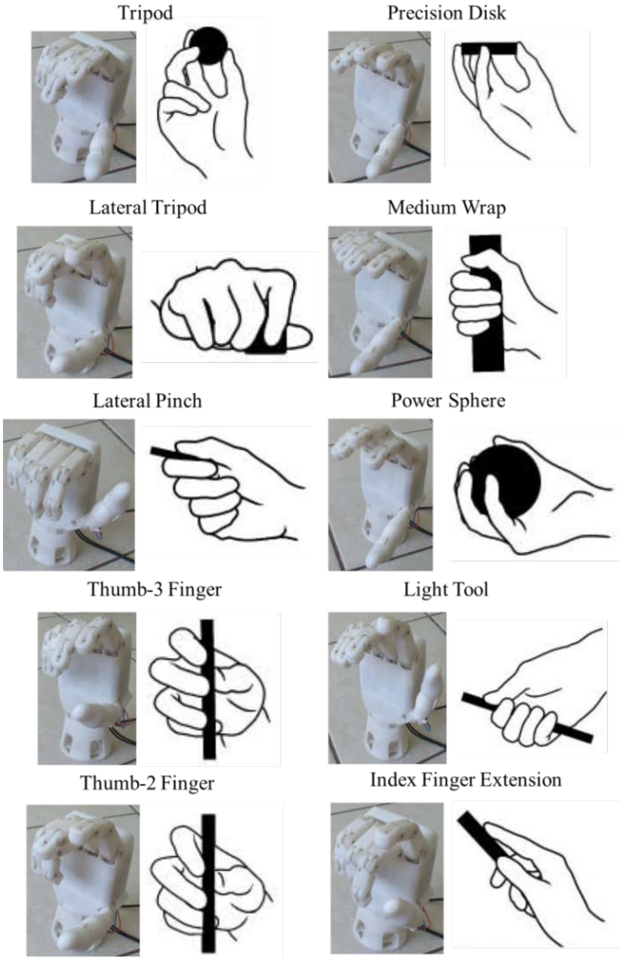

Figure 15 Tested Grasps.

The images of the physical hand grasps show the finger starting positions for the corresponding symbolic grasps. From these positions, the fingers can be closed further into each grasp. It is noticeable that the finger postures are not as natural as the symbols, which can be in the precision disk grasp. In this example, the small finger MCP joint of the symbolic hand has been rotated in flexion, but the other joints are still in extension. Comparatively, the small finger joints of the designed hand are rotated in flexion by a larger amount. This problem can be blamed on the finger joint mechanism, which restricts the finger joints to specific positions relative to the MCP joint position; in other words, they have a pre-set position profile.

A final disparity is that the Touch Hand II fingers cannot abduct or adduct, simply described by the spreading motion. This problem can also be seen in the precision disk grasp; the symbolic fingers abduct to support the disk at equally spaced points around the edges of the disk. Other than these observed discrepancies, the Touch Hand II generally conforms to the desired grasps.

9.2 Compliancy

Compliancy describes the ability of the fingers to wrap around variously shaped objects. Three common household objects were used to check this; an apple, glasses case, and water bottle. The glasses case was grasped in two orientations to vary the finger contact points; figure 16 shows the conducted object grasp tests.

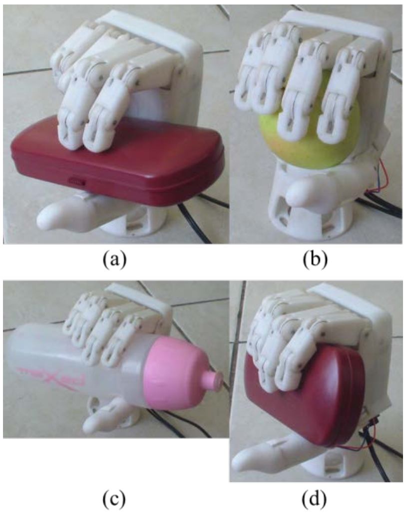

Figure 16 Grasping Objects; (a) glasses case grasp 1, (b) apple, (c) water bottle, (d) glasses case grasp 2.

The first pose of the grasp holding the glasses case shows how the fingers are constrained by the linkage mechanism. Holding the apple shows how all three finger bones of the middle and ring finger contact a round object. The thumb was not as successful with conforming to the object's shape. This issue is a result of the DIP joint of the thumb being in a fixed position. Designing this joint to rotate would enable the thumb to wrap around and support the objects better, by providing more surface contact and less space for the object to move in.

The fingers, however, generally wrapped around the objects such that they could be held in place. This was assisted by the elastic characteristic of the internal cables used for linkages. This elasticity is due to small bends in the cable, and slack being present after the mechanical assembly. Although the motion profile of the fingers are theoretically fixed, this elasticity assists the fingers with slightly altering their theoretical motion profile. When a finger phalanx came in contact with the object, the associated joint would first displace due to the wire elasticity before conforming to the linkage motion constraint. This sequence is advantageous to its compliancy.

9.3 Finger Strength

The finger strength was represented by the maximum torque produced at the MCP joint because this torque applies to the full range of motion of the MCP joint. The maximum MCP joint torque is designed to be the same for the index, middle, ring, and small fingers because the motors and drive trains are identical. This simplified the measurement process in comparison to measuring the finger-tip force throughout the range of motion. The maximum MCP joint torque of each finger was tested by creating an external load as shown in figure 17.

Figure 17 Finger Load Test (Top View).

The hand was placed horizontally across a table, resting with the inside of the palm facing up. A strap attached to a water bottle was fitted onto each of the fingers, close to the MCP joint. The bottle was filled with water before a close command was given. The water quantity was altered until the finger showed only a small amount of movement during maximum torque control. The rated and intermittent limits were tested individually. Using the estimated load force and the lever arm distance of 22 mm, the load bearing torques supplied at the motor output shafts were calculated. These are listed in table 3.

Table 3 Maximum MCP Joint Torques

Finger	Rated Torque [N.mm]	Intermittent Torque [N.mm]
Index	47	72
Middle	49	73
Ring	46	75
Small	50	75

A second method for representing finger strength is by the finger-tip force. The correct equipment for measuring this force was not available; however, an estimate was calculated from the measured MCP torque values. Knowing that the maximum MCP joint torque is applicable to any joint position, and acquiring the minimum finger-tip distance from the MCP joint throughout its range of motion, the maximum finger-tip force can be found by multiplying these two values. This was only done for the index finger, giving an estimated maximum finger-tip force of 1.7 N at a MCP joint position of 104°.

9.4 Grip Strength

Two tests were performed to check the combinational finger grip strength of the hand. These included the power (or power sphere) grasp and the lateral (or lateral pinch) grasp. A similar set-up to the finger strength test was used. The power grasp load test had the strap wrapped over the four fingers used in the grasp; index, middle, ring, and small fingers. These fingers evenly held the load, resulting in the maximum load for the continuous and intermittent case being 4080 g (40.0 N) and 6175 g (60.6 N), respectively, at a lever arm distance of 11.5 mm. The lateral pinch test was done by placing the strap of the connected bottle between the thumb tip and hand using the lateral pinch grasp. This held 540 g (5.3 N) and 817 g (8.0 N) for the rated and intermittent cases, respectively.

9.5 Closing Time

The closing time of the hand was implicitly measured during the positional control testing. Using the fastest speed setting, a graph of speed over time was plotted for a complete close action for each finger; this was done for a close position of 90°. A time of 0.826 s was achieved.

9.6 Mass

The mass of the hand, including the electronics and the wrist, but excluding the socket, was measured to be 486 g. Excluding the socket and wrist, the mass is 451 g.

9.7 Form Factor

The initial concept design was based on 50^{th} percentile anthropometric dimensions, but these changed after accommodating the sizes of the motors and the finger drive mechanisms. The final dimensions are in the 90^{th} percentile data range of males in the ANSUR database [16].

9.8 Amputee Trial

An amputee was fitted with the hand and custom socket to evaluate the aesthetics and mass from a user's perspective. The electronics were not powered during this evaluation because a sEMG control interface between the user and the hand had not been incorporated as yet. A willing amputee, who lost both hands from an electrical accident, can be seen wearing the socket and attached hand in figure 18.

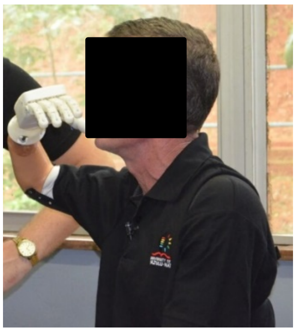

Figure 18 Amputee Testing the Weight and Aesthetics.

The same amputee tested the first version of the hand, the Touch Hand I. He instantly noticed the difference in weight, being lighter than the first version. He was enthusiastic to see the new shape and size of the design, and explained how it had a human-like size and was more aesthetically appealing in comparison to the previous design. One improvement that he recommended was to give the fingers a skin-like surface to grip objects more reliably.

9.9 Power Consumption

The amount of power consumed over a day of use is dependent on the types of tasks performed by the hand, how frequently they are used, and how long each task takes. The type of task will determine the grip force required, hence, the power required. The duration of each task multiplied by the frequency per day gives the time spent for each task over a day. The times per day for each task multiplied by their respective power consumption gives the power capacity requirements for each task per day. Summing these capacities gives a total power capacity requirement per day. This method can be used to select the capacity of a battery pack for a particular individual. For a simple comparison against other hands, the maximum power consumption was determined. Using a variable power supply with a current indicator and voltage of 6 V, the hand was closed in a power grip to its maximum torque capabilities. The maximum current drawn was 2.5 A, multiplied by the voltage, gives a maximum power usage of 15 W.

10 Comparison to Low-Cost and Commercial Alternatives

A number of prosthetic hand characteristics relating to functional performance, aesthetics, structural integrity, and fitment limitations were used to compare five low-cost and two commercial hands (I-limb Ultra Revolution and the Bebionic3), in order to identify problems with low-cost designs. Data for the comparison was recorded and is provided in table 4. Additionally, the best results of each characteristic are bolded. The major observation is that none of the low-cost hands have more than four of the ten characteristics that are similar to or outperform the commercial options. The same characteristics of the Touch Hand II are used to compare the design against the same hands to evaluate its value over other low-cost hands, as well as where improvements are needed to compete with commercial alternatives.

10.1 Closing/Opening Times

The closing and opening times of table 4 are minimum values between full extension of the fingers and a power grip type (full flexion of the fingers with the thumb flexed onto the index finger). The opening and closing time of 0.826 s of the new design is undoubtedly the second shortest, in comparison to all the hands in table 4, but it is still faster than both commercial hands by at least 17 %. It is a drastic improvement of the previous design iteration, which has a 2.0 s closing and opening time. This new shorter time will aid an amputee with grasping and placing objects quickly.

10.2 Actuation and Fitment Limitations

DC motors are the actuators of choice for the hands of table 4, but one of the low-cost hands uses an alternative source of actuation, namely shape memory alloys (SMAs). These alloys can produce forces via joule heating, but are electrically inefficient [11]. A higher number of actuators imply that there are more independently actuated joints available to control closer to realistic motion. Having 6 actuators in the new hand is no different to the previous version, but this is on par with the commercial hands.

Table 4 Comparison of low-cost and commercial prosthetic hands.

Characteristic	[11]	[12]	[13]	[14]	Touch Hand I	I-limb Ultra Revolution	Bebionic3
Closing time[a] [s]	2.1	unknown	unknown	**0.4**	2 [7]	1.2 [3]	1 [15]
Opening time[a]	1.6	unknown	unknown	**0.4**	2 [7]	Unknown	1 [15]
No. of actuators	9 SMA	**22** (17 hobby servos, 5 DC motors)	1 DC motor	5 DC motors	6 DC motors (excl. wrist) [7]	6 dc motors [3]	5 dc motors [15]
Mass [g]	**310**	1548	230 (w/o elect.)	580 g	515 [32]	443-515 [3]	570-598 [15]
Grip strength[b]	Up to 160 N.mm MCP joint torque; 4.5 N finger-tip force @ 110° (MCP joint).	21.2 N peak finger-tip force.	54 N power grip.	20 N peak finger-tip force.	19.5 N power grip; 3.7 N lateral pinch; 8 kg static hook grip. [32]	136 N power grip; **35 N lateral pinch; 90 kg static hook load** [33]	**140.1 N power grip**; 26.5 N lateral pinch; 45 kg static hook grip load. [15]
Max Power usage [W]	140	39.2	**15.6**	60	38.4 [32]	37 [33]	Unknown
Aesthetics	**50th percentile US female dimensions with realistic shapes; 15 DOF.**	Palm width 25% larger than compared human hand; large finger widths; 50th percentile phalange lengths; shiny metal; box-like shapes; exposed wires; 17 DOF (excl. wrist).[c]	Clean design without anthropometric shapes; 3 fingers; 2 DOF.	Bone-like structure with parameterised dimensions; 15 DOF (excl. wrist).	Block-like shapes, large size, exposed electronics; 15 DOF (excl. wrist) [7]	**Unknown dimensions; cosmetic glove; shapes are anthropomorphic; 11 DOF.[c] [3]**	**Unknown dimensions; cosmetic glove; shapes are anthropomorphic; 11 DOF.[c]**
Structural integrity	Fiber-reinforced plastic composite (Duraform HST); large space in palm that reduces strength; no FEA.	Aluminium; no emphasis on structural strength; no FEA.	Aluminium; looks strong without verification; no FEA.	Nickel coated thermoplastic; no FEA.	ABS thermoplastic; FEA design for 3 kg load. [7]	**Aluminium [3]; possibly other material.**	Unknown material.
Fitment limitations	Part of the forearm used by electronics and actuators.	90 % of the human forearm is used by actuation.	**Can be attached at the wrist.**	Actuators in the forearm.	**Can be attached at the wrist, without the wrist module. [7]**	**Can be attached at the wrist [3].**	**Can be attached at the wrist [15].**
Cost	Low-cost emphasised	Low-cost emphasised	**Materials < US$ 50**	Low-cost emphasised	< ZAR 10 661 (materials)	US$ 40 000 (approx.) [6]	US$ 35 000 (approx.) [6]

Note:
a – for power grip; b – finger-tip forces are of index fingers; c – visually estimated

Surprisingly, it is much less than the 22 actuators in one of the low-cost hands [12]. This low-cost hand, however, has other problems as a result of the many actuators; the main issue being that most of the forearm space is used, limiting the range of amputations that are appropriate for the design. The same problem is present in the hand using SMAs. Conclusively, the new design accommodates amputation types up to the wrist, constraining a similar number of actuators as commercial options within the hand.

10.3 Mass

The hand mass determines its weight, thus, how much muscular effort an amputee needs to produce over time during use. Therefore, a lower mass is more appealing to an amputee. One of the low-cost hands of table 4 has a mass of 230 g, but this does not include the electronics. Because of this uncertainty, the hand with a more reliable mass of 310 g was selected as the best. The 230 g mass hand minimises weight by using only one dc motor and having three fingers. These decisions constrain the motion capabilities to a minimum and remove a natural aesthetic appeal. The Touch Hand II balances the number of actuators, and aesthetic appeal, using light-weight, 3D printed ABS plastic, giving a larger mass of 451 g. However, this mass is within the mass range of the I-limb Ultra Revolution (443-515 g), less than the bebionic3 mass range (570-598 g), and is a 12 % reduction on the previous Touch Hand design. It would be valuable to investigate more recent 3D printing materials in an attempt to improve the strength and mass properties of the hand.

10.4 Grip Strength

The grip strength is important for ensuring an amputee can grasp and lift heavy objects. Grip strength is quantified differently between the commercial and low-cost hands of table 4. Commercial hand strength is quantified by the loads applied in specific grasp types, while low-cost hands use finger-tip force and/or finger joint torques. The hook loads are similar to the power grip strength, except the load is held up by non-back-driveable mechanisms, without the actuators being energised.

The new Touch Hand design does not perform well against the other hands in table 4 in terms of grip strength. For the new design, the maximum finger-tip force of 1.7 N at 104°, and MCP joint torque of 117 N.mm are lower than four of the five low-cost hands of table 4. Similarly, the grasp type strength results - which include the 60.6 N power grip, and 8.0 N lateral pinch – are much lower than the commercial values. The static hook load of the new hand was not measureable because the drive mechanisms did not acquire a non-back-driveable design. The Touch Hand II grip strength is only an improvement on the previous version with regards to the power and lateral pinch grasps, but a static hook load is present in the first design.

As a result of the low grip strength, amputees will not be able to hold as heavy objects, or squeeze as much as the other evaluated hands; a characteristic important to amputees [34]. One mistake in the new design was not incorporating a non-back-driveable actuation mechanism. Using this method would enable loads to be held while saving on power consumption. Although the drive mechanisms utilise the space in the hand well, an alternative design should be investigated to increase the grip strength.

10.5 Power Usage

A prosthetic hand requires low capacity batteries to reduce the mass in the socket of an amputee. The new hand design consumes the least maximum power out of all the hands in table 4, just less than the 15.6 W of one of the low-cost hands, and less than half of both commercial options. Even though less power is consumed, it does not justify grip strengths that are less than half of the commercial products. A critical consideration would be increasing the power consumption to improve grip strength, even though a higher battery capacity would be required.

10.6 Aesthetics

The prosthetic hand aesthetics are described by how well it mimics the appearance of a natural human hand, affecting the acceptance of the prosthesis by an amputee. A large advantage of the commercial products over the low-cost options is that they have cosmetic gloves, giving them a realistic feel and skin-tone. The Touch Hand II, unfortunately, does not include such an additional product at this stage, but should be include in the future. An image of each hand considered in table 4 is provided in figure 19 for visual comparison, which compliments the aesthetic comments.

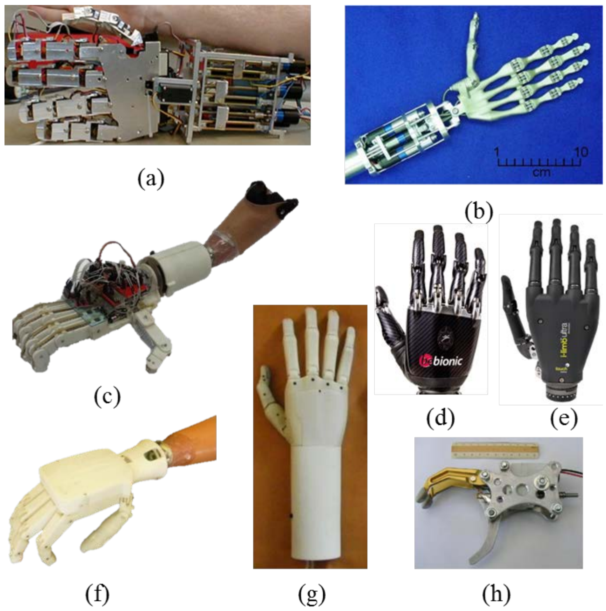

Figure 19 Visual Comparison of the hands in table 4; (a) [12], (b) [14], (c) Touch Hand I, (d) Bebionic3 [15], (e) I-limb Ultra Revolution [3], (f) Touch Hand II, (g) [11], (h) [13].

The combination of 90th percentile anthropometric dimensions from the ANSUR database [16], smooth shapes, and embedded electronics have greatly improved the aesthetics in comparison to the first Touch Hand. However, 50th percentile dimensions would accommodate the proportions of more amputees, such as the SMA based low-cost hand. One other problem of the new Touch Hand is that the back side of the palm protrudes out somewhat relative to the knuckles, degrading its visual appeal. Even though the commercial hands do not have the most DOFs, overall, they maintain the best aesthetics with the SMA based low-cost hand. We have three recommendations for further aesthetic improvements: modify the back palm shape, reduce the dimensions closer to 50th percentile anthropometric data, and investigate further into which and how many DOFs are critical.

10.7 Structural Integrity

The ability of the individual components of the hand to withstand loading conditions describes the structural integrity. Improving the structural integrity of a prosthetic hand will allow it to hold, lift or apply larger loads without failure due to excess mechanical stress; load limits are estimated through simulation and are dependent on material properties and the component design.

No FEA simulation results are available for any of the hands in table 4, except for the Touch Hand I. Assumptions had to be made based on materials and component design. The higher strength of aluminium in comparison to the thermoplastics, and intricate component design of the I-limb Ultra Revoulution made it persuasively the best in terms of structural integrity. A definite improvement on the maximum loads has been made on the previous design of the Touch Hand. The new palm design, with the multiple ribs, allows a 112 N (11.4 kg) load over the knuckles – 3.8 times larger than the first design, with a safety factor of 1.7.

10.8 Costs

The cost of the hand determines whether an amputee can afford to purchase the device. One of the low-cost hand materials in table 4 only amounts to US$ 50 because of its simplistic design, which is several hundred times less than the commercial hands. Unlike the Touch Hand I, only considering material costs, the second version costs also include labour and electricity. Cost estimations were based on the assumption that the hand would be manufactured in South Africa. For labour, the assembly or manufacturing tasks required to be performed by a person were identified. Task times were estimated and appropriately multiplied by skilled (R 250/hr) and unskilled (R 100/hr) pay rates. The computer and 3D printer were considered for direct electricity usage, based on a cost rate of 131.46 c/kWh. The total material cost of the Touch Hand I was previously presented as R 10 661 (US$ 1000) - approximately in June 2014. To avoid confusion of cost comparisons due to changes in exchange rates, the cost of the Touch Hand I and II are given in ZAR in table 5. This summary indicates that the Touch Hand II has reduced material costs by approximately 26 %.

Using the exchange rate as of April 2016, the cost of the new Touch Hand, including labour and electricity, is US$ 1052. Even though this cost is more than the US$ 50 low-cost hand, it is still approximately 35 to 45 times less than the commercial hands in table 4 – a large saving for amputees.

Table 5 Costs of the Touch Hand I and II.

Item	Touch Hand II (June 2015)	Touch Hand I (June 2014)
Material	ZAR 7 850	R 10 661
Labour	R 7 495	n/a
Electricity	R 25,56	n/a
Total	R 15 370,91	n/a

11 Conclusion

This work extends the research of the Touch Hand I by focusing on the mechanical design, producing a second version that is not only an improvement on the first design, but also has more characteristics than a number of other low-cost hands that are competitive with commercial designs. The Touch Hand II has seven out of ten characteristics that are similar to or outperform the two commercial products. Additionally, in comparison to the Touch Hand I, improvements have been made on the closing/opening times, mass, power usage, aesthetics, structural integrity, fitment limitations, and cost. The power grip strength was also an improvement, but not the unpowered static load. These characteristics were achieved by using low-cost electronics, 3D printed material, high speed finger mechanism actuation, and constraining all component designs above the wrist and within the hand. Other considered low-cost hands only have up to four characteristics that are competitive with commercial products. Grip strength, aesthetics, and structural integrity are three characteristics of the new Touch Hand that need improvement to compete with the commercial products.

There are a number of recommendations to address these necessary improvements. Grip strength is the most important to ensure most daily activities are possible. A hasten approach would be increasing the power consumption, directly increasing the mechanical power, hence grip strength. Additional investigation into other finger drive mechanisms would assist. A final recommendation for grip strength is to use a non-back-driveable actuation mechanism to enable the fingers to hold external loads without powering the motors. The aesthetics can be improved by removing the slight protrusion of the back of the palm, reducing the dimensions closer to 50th percentile anthropometric data, and producing a realistic cosmetic glove. This glove should also stop objects from slipping over the plastic hand surface during grasps. The structural integrity could be improved by investigating new 3D printing materials or materials useable with other low-cost methods. An ultimate but critical area of research would be designing and integrating a user interface to the hand for intuitive control by an amputee. The project could be taken further by incorporating other attachable sections of an arm.

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