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Authors
Lim, Daniel
Georgiou, Thomás
Bhardwaj, Aashish
et al.

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CUSTOMIZATION OF A 3D PRINTED PROSTHETIC FINGER USING PARAMETRIC MODELING

Daniel Lim*
Mechanical Engineering
University of California, Berkeley
Berkeley, California 94720
Email: limdan7@berkeley.edu

Thomás Georgiou
Mechanical Engineering
University of California, Berkeley
Berkeley, California 94720
Email: tgeorgiou@berkeley.edu

Aashish Bhardwaj
Bioengineering
University of California, Berkeley
Berkeley, California 94720
Email: aashishb@berkeley.edu

Grace D. O'Connell
Mechanical Engineering
University of California, Berkeley
Berkeley, California 94720
Email: g.oconnell@berkeley.edu

Alice M. Agogino
Mechanical Engineering
University of California, Berkeley
Berkeley, California 94720
Email: agogino@berkeley.edu

ABSTRACT

Prosthetic limbs and assistive devices require customization to effectively meet the needs of users. Despite the expense and hassle involved in procuring a prosthetic, 56% of people with limb loss end up abandoning their devices [1]. Acceptance of these devices is contingent on the comfort of the user, which depends heavily on the size, weight, and overall aesthetic of the device. As seen in numerous applications, parametric modeling can be utilized to produce medical devices that are specific to the patient's needs. However, current 3D printed upper limb prosthetics use uniform scaling to fit the prostheses to different users.

In this paper, we propose a parametric modeling method for designing prosthetic fingers. We show that a prosthetic finger designed using parametric modeling has a range of motion (ROM) (path of the finger tip) that closely aligns with the digit's natural path. We also show that the ROM produced by a uniformly scaled prosthetic poorly matches the natural ROM of the finger. To test this, finger width and length measurements were collected from 50 adults between the ages of 18-30. It was determined that there is negligible correlation between the length and width of the index (D2) digit among the participants.

Using both the highest and the lowest length to width ratio found among the participants, a prosthetic finger was designed using a parametric model and fabricated using additive manufacturing. The mechanical design of the prosthetic finger utilized a crossed four bar linkage mechanism and its ROM was determined by Freudenstein's equations. By simulating the different paths of the fingers, we demonstrate that parametrically modeled fingers outperform uniformly scaled fingers at matching a natural digit's path.

KEYWORDS

Additive manufacturing, Parametric modeling, Mass Customization, Prosthetic Hand

1. INTRODUCTION

Over 541,000 people in the United States are afflicted with upper limb amputation. Common causes of upper limb amputation include vascular disease, infectious disease, and traumatic injury. This number is expected to double by 2050 [2].

*Address all correspondence to this author.

In order to assist this population, two types of prostheses have been developed: passive devices (worn mainly for aesthetic purposes) and active devices [3]. Active devices can be subdivided into two categories: externally-powered and body-powered devices. Although externally-powered prostheses utilizing cutting-edge technologies (e.g., electromyography [EMG], electroencephalography [EEG], neural interfaces) have been popular in the research field, body-powered prosthetic devices are popular with patients due to their light weight, intuitive control, and ease of maintenance [4] [5].

Current finger prostheses have typically been designed with aesthetics in mind and have significant functional limitations. For many patients, the addition of passive and active functionality to their prostheses would be beneficial. Previous attempts to design functionally active finger prostheses have been conducted with some success [6]. Many active prostheses are simply scaled uniformly to match the patient's hand sizes [7]. However this is not always an ideal fit for the patient because of the large variety of hand sizes present in the population.

3D printing has the potential to provide personalized prosthetic and assistive devices. Unfortunately, many 3D printable designs can only be scaled uniformly to match one of the user's dimensions. This can result in excessive or insufficient length across all the other dimensions. We sought to quantify this effect in index finger prostheses and use parametric modeling in our design.

Parametric modeling is a powerful mass customization method in the medical field as it helps automation for generating various customized designs. Amirjani et al. [8] applied this parametric approach towards the design of artherosclerotic stents, and Puértolas et al. [9] demonstrated that custom colonic stents can be developed by parameterizing features such as the diameter and length of the stent, and number of grooves. Additionally, in the field of orthopedics, George and Kumar [10] have proposed a parametric model for the design of custom hip implants. As noted before, customizability is required for a user to accept a prosthesis. Therefore, our team used a parametric approach to design and customize prosthetic fingers.

In this paper, we present length and width measurements of the index finger (D2) and propose a body-powered prosthetic finger design for the index finger. This study has three main aims: (1) To examine the relationship between the width and length of an index finger, (2) To present a parametric model for an index finger prostheses that will better match the original finger's size and range of motion. (3) To fabricate models from the measurements to validate the feasibility and assembly using additive manufacturing.

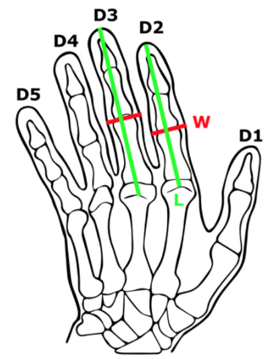

FIGURE 1. Length and width measurement of D2 and D3 fingers

2. METHODS

2.1 Hand Measurements

We recruited 50 participants, male and female, between the ages of 18-30 without any physical deformities or previous history of hand trauma for this study. Participants were contacted via word of mouth and were anonymized for this study. After taking informed consent, the length and width of the index (2D) finger on the right hands of each individual were taken using digital calipers accurate to 0.01mm (Fig. 1).

The measuring errors introduced by use of calipers have negligible impact on the observed coefficients of variation (CV = standard deviation/group mean) between individuals [11]. To eliminate interobserver error, all digits were measured by one observer. The length of the D2 digit were measured from the midpoint of each metacarpophalangeal (MCP) joint crease to the tip of each finger tip. Finger width was measured as the width of the proximal interphalangeal (PIP) joint of each finger (Fig. 1). We assumed that age, gender and handedness had no effects on absolute or relative ratio of digit lengths over digit widths.

2.2. Mechanical Design

Several groups have conducted prosthetic hand and robotic finger research for the above wrist or transradial amputation population [12]. However, 61% of the upper limb amputee population have transcarpal amputations, partial finger amputations that current prosthetic hand research and designs aimed for above wrist amputation cannot provide a solution to [2].

Our mechanical design objectives were to 1) design a body-powered prosthetic finger that uses the partial hand movement of the users. 2) Enable motion for abduction and adduction of the distal phalange that mimics the 1 DOF proximal phalangeal joint, and 3) analyze the range of motion (ROM) of a regular finger for pinching (MCP joint angle from 5 °- 42.5 °) and holding grip configurations (42.5 °- 80 °) [13].

Prosthetic hands have a variety of actuation mechanisms in-

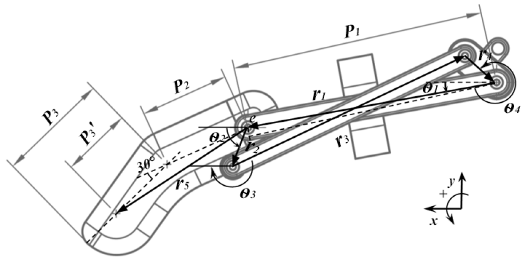

FIGURE 2. Crossed Four-links in the prosthetic finger design

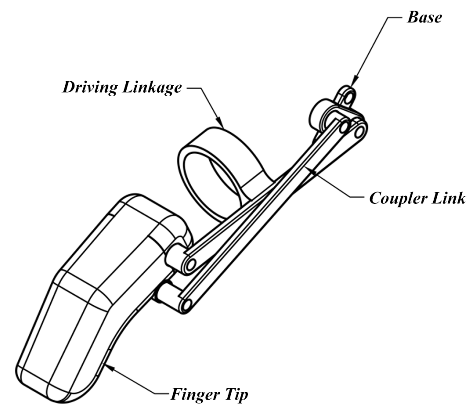

FIGURE 3. Perspective view of the prosthetic finger with individual components labeled (base, driving linkage, coupler link, finger tip)

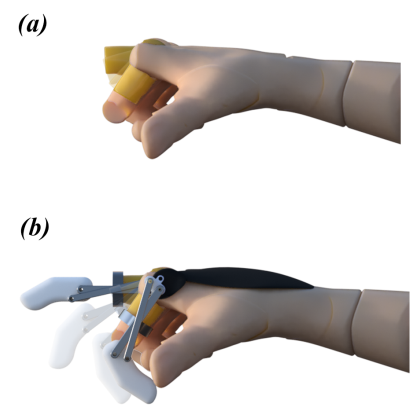

FIGURE 4. (a) Simulation of an amputated index finger marked as yellow (b) Simulation of the prosthetic finger from the residual index finger

cluding tendons, linkages, and gears [12]. One popular actuation method for prosthetic fingers is the crossed four bar linkage mechanism that translates the movement of the driving linkages (from MCP joint) to the fingertip (proximal phalange). Haulin et al. [13] presented linkage ratios that enable actuation of the prosthetic finger without a dead point during the pinching or the cylindrical grips. Our design used these numerical ratios of the lengths in the linkage design to generate identical angle changes regardless of the link sizes. Figure 2 shows the crossed four links mechanism in the finger where the length ratios and equations are based on the research by Haulin et al [13] (r_1 = 44.54mm , r_2 = 7.58mm, r_3 = 45.30mm, r_4 = 7.42mm, θ_4 = 338 °, eccentricity = 2mm).

For a given point i, the addition of all the vectors of the links is as follows Eq. (1).

$$\vec{R}1+\vec{R}2+\vec{R}3+\vec{R}4=0 \tag{1}$$

Freudenstein's equation can be derived from the Eq (1) [13]:

$$\begin{aligned} r_1\cos\theta_{1i}+r_2\cos\theta_{2i}+r_3\cos\theta_{3i}-r_4\cos\theta_4=0, \\ r_1\sin\theta_{1i}+r_2\sin\theta_{2i}+r_3\sin\theta_{3i}-r_4\sin\theta_4=0 \end{aligned} \tag{2}$$

Removing θ_{3i} by combining Eq. 2 derives the relationship between θ_{1i} (input, driving linkage) and θ_{2i} (output, finger tip) as shown in Eq. 3. By replacing r_2, r_3, r_4 by the multiplier of r_1 from the length provided by Haulin et al. [13] generates Eq. 4 of θ_{1i} and θ_{2i} which is independent from the length r_1.

$$\begin{aligned} &\frac{r_4}{r_2}\cos(\theta_{1i}-\theta_4)+\frac{r_4}{r_1}\cos(\theta_{2i}-\theta_4)-\frac{{r_1}^2+{r_2}^2-{r_3}^2+{r_4}^2}{2r_1r_2} \\ &=\cos(\theta_{1i}-\theta_{2i}) \end{aligned} \tag{3}$$

$$\begin{aligned} &0.979\cos(\theta_{1i}-338^\circ)+0.167\cos(\theta_{2i}-338^\circ)-0.0655 \\ &=\cos(\theta_{1i}-\theta_{2i}) \end{aligned} \tag{4}$$

A solid model was then developed based on the linkage ratios and phalaneges ratio discussed above, where the whole assembly consists of four main parts as shown in Fig. 3. 1) *Base (r_4)*, is grounded above the user's MCP joint by a glove or thermoplastic harness. 2) *Driving Linkage (r_1)* where the user can slide their residual amputated finger into the ring component. 3) *Fingertip (r_2)* is where the end point is attached in order to produce grips, and 4) *Coupler link (r_3)* connects the other linkages. The Computer-Aided-Design (CAD) of the parts were designed in Autodesk Fusion 360.

The user actuates the device by moving the driving linkage with his or her residual finger. Figure 4 demonstrates the actuation of the device by moving the MCP joint (residual finger part colored in yellow on 4(a)). The hand simulator was based on an open source design 'Adam's hand' from GrabCAD [14].

2.3. Range of Motion Comparison

A reference finger's ROM equation defined by Guo et al. [15] was compared to the prosthetic fingers' ROM. To match the regular finger dimensions provided by Guo et al to our prosthetic finger, the phalanges lengths (Fig. 2) were set as: P_1 = 44.5mm, P_2 = 29.2mm, P_3' =17.3mm, where P_3' is the effective length of P_3 [13] [15]. In order to normalize the equations by the full finger length (L = P_1+P_2+P_3'), we normalized P_1, P_2, P_3', and e (eccentricity) as 44.5/91L, 29.2/91L, 17.3/91L, 2/91L respectively.

From these parameters the equation for R_5, the vector from the rotational axis of driving linkage to the effective finger tip (Fig. 2), is Eq. 5. By adding this vector to R_1, the vector from the base to the rotational axis of the finger tip (Fig. 2), the ROM of the effective finger is fully described.

$$\begin{aligned}\vec{R}_5 &= 0.499L\{\cos(\theta_{2i}+11.99^\circ)i-\sin(\theta_{2i}+11.99^\circ)j\}\\ \vec{R}_1 &= \frac{44.54}{91}L\{\cos(\theta_{1i}+2.53^\circ)i-\sin(\theta_{1i}+2.53^\circ)j\}\end{aligned} \tag{5}$$

$$\begin{aligned}x_i &= L\{0.499\cos(\theta_{2i}+11.99^\circ)+\frac{44.54}{91}\cos(\theta_{1i}+2.53^\circ)\}\\ y_i &= -L\{0.499\sin(\theta_{2i}+11.99^\circ)+\frac{44.54}{91}\sin(\theta_{1i}+2.53^\circ)\}\end{aligned} \tag{6}$$

Using Eq. 5 and Eq. 6, we plotted the ROM of the prosthetic finger using Matlab. Input angle (θ_1) was represented as a uniformly incremented array that ranged from 0°to 80°. The increment angle was chosen to be 0.01°. This array inputted into Eq.4 using vpasolve to generate the θ_2 values. The θ_1 and θ_2 arrays were used to solve Eq. 6. The x and y values generated were then normalized as a percent of L and plotted with Matlab.

Our reference finger path was based on the equations provided by Guo et al. for two grips (pinching and holding) of a regular finger [15]. θ_1, θ_2, θ_3 represent the MCP joint angle, distal interphalangeal (DIP) joint angle, and PIP joint angle respectively.

For the pinched grip ($5^\circ \le \theta_1 < 42.5^\circ$),

$$\begin{aligned}\theta_2 &= 2.45\theta_1\\ \theta_3 &= 3.35\theta_1\\ x_s &= P_1\cos\theta 1+P_2\cos\theta 2+P_3'\cos\theta 3\\ y_s &= P_1\sin\theta 1+P_2\sin\theta 2+P_3'\sin\theta 3\end{aligned} \tag{7}$$

For the holding grip ($42.5^\circ \le \theta_1 < 80^\circ$),

$$\begin{aligned}\theta_2 &= 2.45\theta_1+19.12^\circ\\ \theta_3 &= 3.35\theta_1\\ x_s &= P_1\cos\theta 1+P_2\cos\theta 2+P_3'\cos\theta 3\\ y_s &= P_1\sin\theta 1+P_2\sin\theta 2+P_3'\sin\theta 3\end{aligned} \tag{8}$$

P_1, P_2, P_3' were normalized as 44.5/91L, 29.2/91L, 17.3/91L in order to plot the reference ROM as a percent of the target length.

The x value (x_s) and y value (y_s) of the reference path were solved for each value of the θ_1 array used previously. The normalized x_s and y_s were then plotted with Matlab adjacent to the ROMs of the prosthetic fingers. To quantitatively compare similarity of each of the prosthetic finger paths to the regular finger path, the minimum distance between the reference path and the prosthetic's path at each point of the prosthetic finger path was calculated. We assumed that a prosthetic finger that had the smallest mean distance difference and a relatively low standard deviation of minimum distance best matched the path of a regular finger.

2.4. Parametric Design

Parametric solid modeling techniques can be used to create a product family from a single design file by changing a few parameters in the original solid model [16]. Mathematical approaches require parameterizing the key features in the equations, such as distances, lengths, tangencies, angles, etc. This approach allows input based on customizable measurements to be used as dimensional constraints and to create a unique design for each subject.

Conventional prosthetic hand design and fabrication requires one-on-one fitting and customization by a trained prosthetist. Otherwise, users are forced to default to hand components that come in standardized sizes. Additive manufacturing opens up the possibility of customized prosthetic hand for individual hands. Zuniga et al. [7] proposed a Cyborg Beast hand which is widely used in the open source community. Cyborg Beast is a body-powered prosthetic hand actuated from the wrist, built for people with congenital hand deficiency.

Even though the measurements for the palm width, forearm length, hand length, and range of motions are made, a major

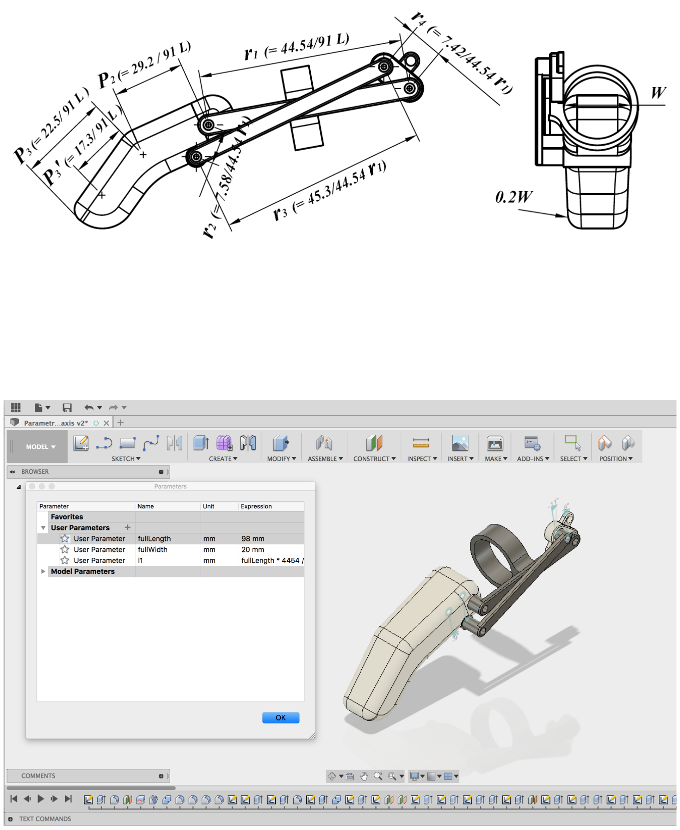

FIGURE 5. Drawing of dimensional contraints set from the designated parameters; length (L) and width (W) (top), User interface showing parametric modeling of prosthetic finger design using Autodesk Fusion 360 (bottom)

drawback of the Cyborg Beast is that users can only fit the hand to their dimensions by uniformly scaling the model. This means that users are forced to use a hand that fits the average of their hand sizes rather than a hand which fits each dimension well. Our goal is to present a mechanical finger design optimized for parametric design and to demonstrate that parametric modeling is superior to uniform scaling for mass customization by producing individually tailored prostheses.

The width (denoted as W), and finger length (denoted as L), were chosen as two dimensions for the parametric design. In the design, length related components; phalanges length and the length of the linkages were set as percentage of the full finger length (L). The ratio between phalanges was set as 17.3:29.2:44.5 for the effective length of distal (DP), intermediate (IP) and proximal phalanges (PP) respectively [13]. Each sections was presented as a fraction of L; 10/46 L (DP), 13/46 L

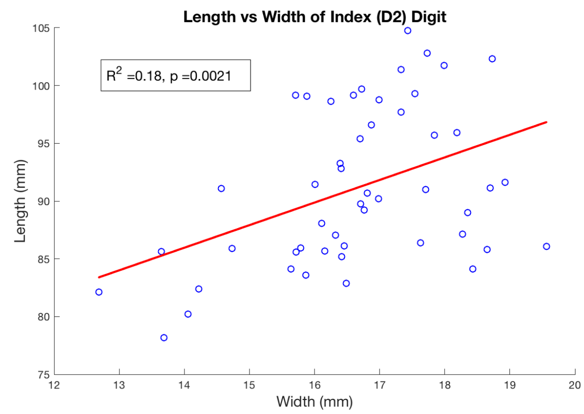

FIGURE 6. Length versus width of D2 digit for 50 subjects with linear curve fit. $R^2 = 0.18$.

(IP), and 23/46 L (PP) as shown in Fig. 5.

The linkage lengths were also based on the finger length (L), where the driving linkage length (r_1) is proportional to the full finger length 44.54/91 L [13]. Other linkage components lengths were set as multiplier of r_1 by following the crossed four bar links mechanism explained in the mechanical design section.

The circumference of the ring size of the driving links, width of the finger tip, and the fillet of the finger radius were set as multipliers of the input width of the finger (W). Other parts that required interface with standardized parts were constrained to a fixed dimension (5mm).

The design was modeled using Autodesk Fusion 360 CAD software by setting the User specified parameters in 'Modify' > 'Change parameters' windows. The User Interface is shown in the Fig. 5 where the finger length (L) was defined as fingerLength and width (W) as fingerWidth as two parameters. These parameters were used as dimensions to draft out the design that was introduced above. With this approach, the designer can simply change the parameters independently fit the users input instantly (length and width) in contrast to the uniform scaled method where parameters are dependent on each other.

3. Results

3.1. Relationship between D2 finger width and length

The average length, width and ratio of length to width of the D2 was 90.9mm, 16.9mm, and 5.41 respectively across the 50 subjects. Using the average length to width ratio, we calculated the difference between anticipated length of each subject's D2 digit and their actual finger length as a percentage.

Measurements of the D2 finger width and length were plotted and fit with a linear curve as shown in Fig. 6. Correlation coefficient ($R^2 = 0.18$) and p-value ($p = 0.021$) show that there is weak to no correlation between D2 length and width. This

Length difference (x) in percentage	Number of measurements	Number of measurements in percentage
20% ≦ x < 25%	2	4%
15% ≦ x < 20%	2	4%
10% ≦ x < 15%	4	8%
5% ≦ x < 10%	4	8%
-5% ≦ x < 5%	24	48%
-10% ≦ x <-5%	9	18%
-15% ≦ x < -10%	5	10%

TABLE 1. Assorted length difference in percentage of 50 measurements (uniformly scaled and measurements length)

further illustrates the need to use parametrized models because there is no consistant relationship between relative finger sizes.

3.2. Comparison of uniformly scaled and parametric scaled models

From the measurements, we assumed building a prosthetic finger for the participants index finger using two different design methods: uniform scaling and parametric modeling. For the uniform scaling method, a reference model was created using an average of the length (90.9mm) and width (16.9mm). As current 3D printed prosthetic hands use a single parameter [7] for scaling the reference model, we scaled the prosthetic finger from the width measurement of the finger.

Using width for scaling ensures that the residual finger fits the ring part of the device. From this reference, the files were exported into the STL file format, and scaled uniformly using 3D printing slicer software CURA to retrieve the length of the index finger length L (Fig. 7). For the parametric modeling, two parameters were input into the Autodesk Fusion 360 parameters user interface (Fig. 5), as fingerLength and fingerWidth, then exported into STL files.

The extracted measurements of prosthetic finger length using parametric modeling and uniform scaling were used to compare the ROM with an original finger movement. Length difference with the measured finger length and the design were calculated, then assorted into 5% range to set the ROM differences in percentage.

For the uniformly scaled model, 48% of the designed finger length were within the range of -5% to 5% of the actual finger length (Table 1). However, 24% of the designed finger length were longer than 5% of the actual length and 28% of the population were shorter than -5% of actual length the range varied from -14.99% up to 25% of the reference length. On the other hand, parametric modeled fingers' length were always in the -5% to 5% range as the width and the length were independent, thus being able to change the length to the expected value.

Figure 8 shows a comparison between the parametric model

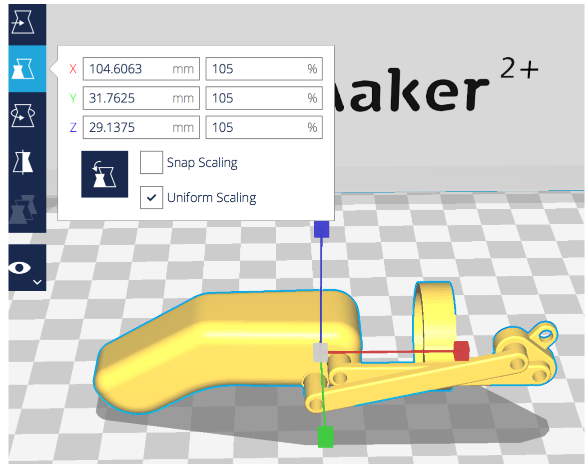

FIGURE 7. The STL file of the average model was uniformly scaled to fit the width of the measurement

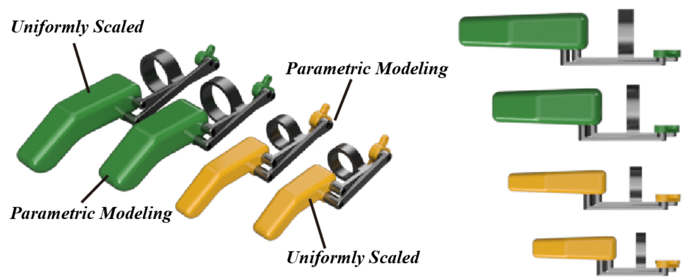

FIGURE 8. Comparison between uniformly scaled and parametric modeled CAD files using two measurements. The green models used an index finger of length 86.06 mm and a width of 19.56mm, length/width ratio; 6.47. The yellow model used an index of finger of length 82.11 mm and a width of 12.69mm, length/width ratio; 4.40.

and a uniformly scaled model. Two index fingers which had a small 3.95 mm length difference (86.06 mm to 82.11mm) and a large difference in their length / width ratio were modeled and compared. The green model was for a finger with a small length to width ratio (4.40). The outer finger represents a uniformly scaled model (the resulting finger was 105.82mm) and the inner finger used the parametric model (resulting finger was 86.06mm). The yellow colored model represents an index finger with a high length to width ratio (6.47), the outside model represents a uniformly scaled model (resulting finger was 68.65mm) and the inner finger used a parametric designed model (resulting finger was 82.11mm). In each case, the parametric model matched original length of the finger. Using a uniformly scaled model could make a 37.17mm(105.82mm - 68.65mm) length difference rather than the actual difference of 3.95mm.

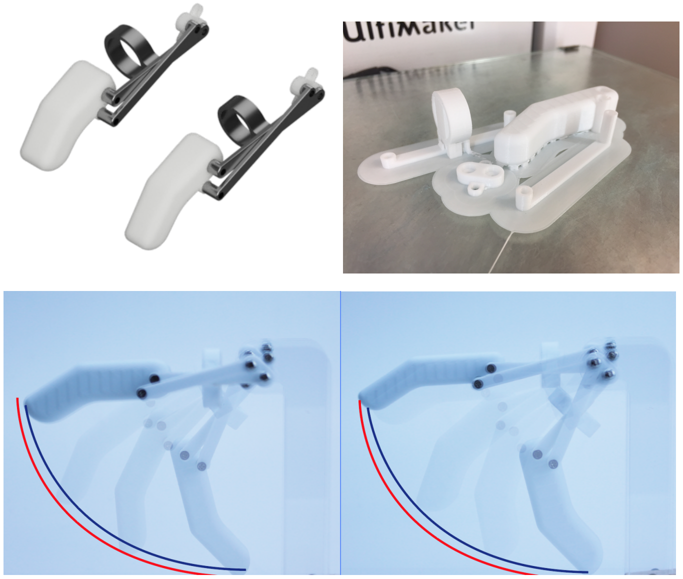

FIGURE 9. CAD model of highest and lowest ratio from the measurements and 3D printed parts from Ultimaker (top), and assembled fingers in action showing similar ROMs from different ratio; red line for 6.47 ratio and blue line 4.40 ratio (bottom)

3.3. Fabrication of the prosthetic finger

To validate the feasibility of the parametric modeled design, two CAD models of the prosthetic finger were designed from the measurements that showed the highest length / width ratio (6.47, from width: 12.69mm, length: 82.11mm) and the lowest length / width ratio (4.40, from width: 19.56mm and length: 86.06m). The measurements were used as parameters in Autodesk Fusion 360 (Fig. 5) to generate individual CAD models. Four different STL files for parts (base, finger tip, driving linkage, and coupler link) were exported and prepared for 3D printing through the slicer software (CURA).

A fused deposition 3D printer, Ultimkaer 2.0+, was used for the fabrication of parts. Four parts were printed all at the same time, with the following setting; brim for the build plate adhesion, supports generated for the overhangs, 0.15mm of layer thickness, PLA for the material, 60mm/s of printing speed and 20% infill. Two different designs each took 82 minutes (lowest ratio) and 93 minutes (highest ratio) for the total printing time. All the parts were printed and assembled using 4-40 screws with different length based on the part configuration. Assembled prosthetic fingers are shown in Fig. 9.

3.4. ROM comparison

Figure 10 shows the results from the MATLAB simulations of the regular finger and prosthetic finger paths. A parametric

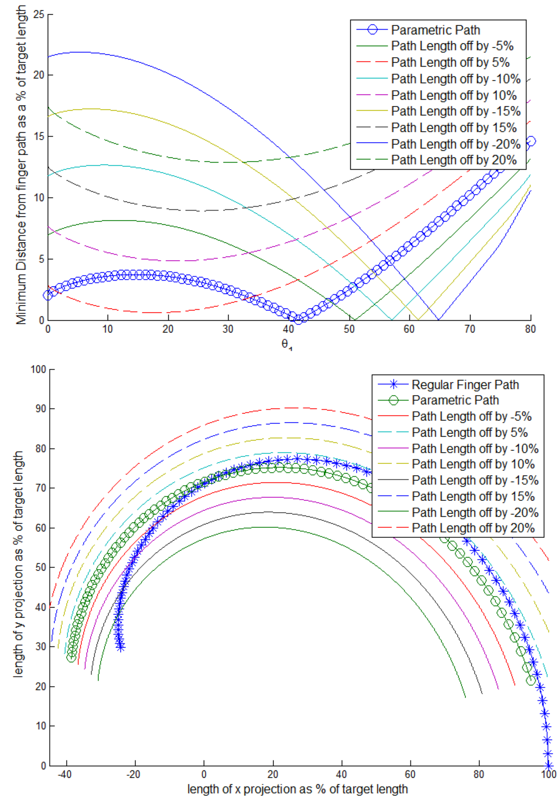

FIGURE 10. Minimum distance from reference finger ROM as a function of input angle (θ_1) plotted for different prosthetic finger lengths (top) and ROM plots for different prosthetic finger lengths (bottom). The target length is the reference finger's length

modeled finger, which would have the same length as the target length, had a lower mean minimum distance than fingers whose lengths were 5% above or below the target length. In addition, the parametric modeled finger had a relatively low standard deviation indicating there are no sharp deviations from regular finger path throughout the length of its ROM.

As the deviation from the target length increased the mismatch between the ROM of the regular finger and prosthetic finger paths became more pronounced. As our measurements demonstrate, uniform scaling can sometimes lead to mismatches that range from -15% to +25%. In such cases the average difference between the paths of the prosthetic and a regular finger would be 10.25% to 18.73% respectively (Table 2). Such a large difference between the natural path and the path of the prosthetic may result in decreased ability to grip or pinch objects. These grips are a staple of everyday hand use and thus any prosthetic finger that cannot execute these grips will have poor efficacy. Even a 10% length difference results in an average path offset of approximately 8-9%. If 52% of the population has fingers di-

Length difference in percentage	Mean distance difference (%)	Standard Deviation (%)
25%	18.73	1.88
20%	15.29	2.36
15%	11.88	3.05
10%	8.49	3.85
5%	5.13	4.79
0%	4.64	3.66
-5%	6.04	2.99
-10%	7.98	3.97
-15%	10.25	5.59

TABLE 2. Mean minimum distances and the standard deviation from the length difference with the reference finger length

mensions which would cause a uniformly scaled model to miss its target length by +/- 5%, uniformly scaled fingers may be insufficient for a significant portion of the finger amputee population.

4. Conclusion

We examined the correlation between width and length of the finger from 50 measurements of individuals participants. The results show that there is a weak or no correlation between two parameters with R^2=0.18 and p value of 0.0021. A prosthetic finger design was proposed for transcarpal amputees who remain partial finger movement on the MCP joint.

We implemented parametric modeling to control two parameters (width and length) independently. A crossed four linkage mechanism was used to generate a single degree of freedom, with the ROM equation of effective finger tip derived from the Freudenstein's equation.

The ROM determined from parametric modeling, where the length was identical to the actual finger length, was compared to the uniformly scaled models where previous 3D printed upper limb prosthetic devices used for customization. Fifty-two percent of the population's uniformly scaled models absolute length differences were over 5% the original length. This meant at least 5% to 15% off from the expected ROM which was calculated from % mean minimum distance from natural finger ROM, showing that parametric modeling enables optimization of the ROM path by removing the dependencies between parameters.

Two measurements that showed the highest and the lowest length to width ratio were used to create a physical prosthetic finger. Parts were fabricated with 3D printing to ensure the feasibility of changing parameters for the automated CAD design and completeness of the model's assembly.

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