Rapid and Flexible 3D printed Finger Prostheses with Soft Fingertips: Technique and Clinical Application

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ABSTRACT We present a method for fabricating passive finger prostheses with soft fingertips by utilizing 3D scanning and 3D printing with flexible filament. The proposed method uses flexible filament and multi-process printing at varying infill levels to provide soft fingertips to emulate biological fingers. The proposed method also enables rapid prototyping of finger prostheses, and the flexibility to change interphalangeal joint angles to fit the prostheses for different manipulation and occupational therapy tasks. The entire process designing and fabricated the prostheses can be conducted in one day. The presented technique uses scan data of the intact side fingers to provide the shape and contour of the finger prostheses, while the socket is designed based on the scan data of the amputation side. The paper presents the developed technique and its clinical application. Experiments are conducted to measure the stiffness of the printed material at varying infill levels and the stiffness of the printed fingertips. The results are compared to measurements of biological fingertip stiffness from the literature. The clinical application includes two cases, one case with distal phalanx loss on the thumb, index, and middle fingers, and one case with distal and middle phalanx loss on the middle and ring fingers. Fitting was successful on both recipients and they were both able to use the prostheses successfully.

INDEX TERMS Prosthetic fingers; 3D printing; 3D scanning; Computer Aided Design.

I. INTRODUCTION

Finger amputation is the most common amputation of the limbs [1, 2]. Most persons with amputation are supported by public social programs such as welfare systems or worker’s compensation. However, prostheses for patients with finger amputation are frequently excluded from such social programs. We focus in this work on patients with amputated fingers using 3D printing to fabricate the finger prostheses.

Partial or complete finger loss are commonly addressed with silicone rubber prostheses [3, 4, 5, 6, 7]. These prostheses are passive and aesthetic since the remaining hand’s degrees of freedom are adequate to carry on daily tasks, especially for partial digit loss.

The process of fabricating a silicone-material finger prosthesis requires manual skill for the casting process and expertise with the casting materials and methods. The shape of the finger prosthesis is obtained through sculpting or by taking a cast from a donor that has a similar finger shape to the recipient. The process also does not allow for easy adjustment of the finger shape or inter-phalangeal joint angles at the resting position.

In recent years methods of additive manufacturing, 3D printing, are increasingly being utilized in the manufacturing of affordable full and partial hand prostheses [8, 9, 10]. The advantages of 3D printed prosthetic hands in terms of user acceptance, functionality and durability are still lacking evidence [8]. However, 3D printing has a clear advantage when combined with 3D scanning to create personalized sockets and prostheses, especially for rehabilitation as transitional stage prostheses. Cabibihan J.J. [11] proposed integrating
digital tools by utilizing Computer Tomography (CT) images in the design process of finger prosthesis. In their approach Cabibihan J.J. used the CT images of the region of the affected and the nonaffected fingers to design the socket and finger mould. This enabled remote collaboration to design and fabricate the prosthesis and reduced the time needed to design and fabricate the prosthesis to less than one week.

The mechanical characteristics of human fingers are critical to enabling the dexterous manipulation of objects. In particular, the softness of the human fingertips changes the contact area depending on the shape of the grasped object, adjust the compliance between the fingers and the object, and provide an additional friction force on the object [12]. These properties are missing from current prosthetic hands and prosthetic fingers. Recent research on soft robotics investigated finger compliance in total [13], [14], and have demonstrated the advantages of finger compliance in object grasping and manipulation. Finger compliance, however, cannot replace the role of the soft fingertips mentioned earlier. Research that created soft distal phalange segment with silicon casting has also been conducted to predict the gripping force with the prosthetic hand and fingers, but the fingertip stiffness has not been evaluated or compared to human fingertips. To the best of our knowledge, there have been no works that explicitly consider the fingertip stiffness for 3D printed finger prostheses and demonstrate their clinical application.

In this work, we introduce a new technique for fabricating passive finger prostheses by utilizing digital tools; a 3D scanner, CAD software, and a 3D printer (Figure 1). In the proposed method we use flexible material to fabricate the finger prostheses, and we devise methods to obtain stiffness on the prostheses and fingertips that mimic biological fingers. The proposed method also enjoys the advantages of digital fabrication, which means the finger prostheses can be fabricated rapidly for daily use and occupational therapy. The shape and posture of the fabricated fingers can be iterated on and adjusted to fit the user’s preference, and the production cost will be reduced.

The process of designing, fabricating, and prescribing the prostheses is integrated by its nature. Therefore, works describing new fabrication techniques attempt to cover the design, fabrication, and brief case studies as well [6, 7, 9, 11]. This work follows a similar structure. However, since the fabrication method proposed in this work introduces a feature that might have functional advantage in addition to the aesthetic appearance, we also included functional evaluation using the Action Research Arm Test.

The contribution of this work is threefold: 1. Using the properties of the flexible filament and design/printing techniques to obtain soft fingertips and improve the functionality of the prosthesis. 2. Using the scan data of both sides’ hands, amputation side, and intact side, to design the socket and the finger’s shape together. 3. Demonstrate the use of the designed prostheses with two recipients.

In the following sections, we present the detailed process of fabricating the finger prostheses and the clinical application with two recipients.

II. METHODS

Here we detail the process of fabricating the finger prostheses for persons with partial finger loss. The technique is described in a tutorial-like format to make it possible to replicate and adapt this method for different cases and recipients, due to the large individual differences of partial finger prostheses recipients. The developed technique consists of three main steps, Scanning, Design, and Printing.

A. SCANNING

In the first step, we acquire digital data from both hands of the recipient with a 3D scanner, CAD software, and a 3D printer (Figure 1). In the proposed method we use flexible material to fabricate the finger prostheses, and we devise methods to obtain stiffness on the prostheses and fingertips that mimic biological fingers. The proposed method also enjoys the advantages of digital fabrication, which means the finger prostheses can be fabricated rapidly for daily use and occupational therapy. The shape and posture of the fabricated fingers can be iterated on and adjusted to fit the user’s preference, and the production cost will be reduced.

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II. METHODS

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A. SCANNING

In the first step, we acquire digital data from both hands of the recipient with a 3D scanner. The scanner used was Eva (Artec 3D corp.). The scan data of the amputation-side hand is used to create the socket part of the prosthesis, and the scan data of the intact hand is used to acquire the shape of the finger prosthesis. The scan data was pre-processed with the 3D scanner software (Artec Studio 11, Artec 3D corp.) to create workable 3D data from the scans.

Scanning a person’s hand and fingers can prove to be a challenging task. The main issues are occlusions between the fingers and the lack of anchor points for the scanner’s tracking software to rely on. The authors found the following tips beneficial to acquiring better scans:
The data obtained from the 3D scanner software is then exported as STL files to the design software. The design software used was MeshMixer v 3.5.474 (Autodesk, Inc.). The data of the intact side fingers was cropped and reflected about the sagittal plane to create the shape of the finger prostheses (Figure 2, i). The data of the amputation side was cropped to form the socket shape. The two parts were aligned manually with reference to the scan of the intact side hand (Figure 2, ii). The two parts were then joined using the "join" function in MeshMixer (Figure 2, iii). Up to this point, all the data is in the form of shells; with no thickness. The shells are then thickened with the extrude function outwards of the finger prostheses, normal to the shell's surface, with an amount of 0.8 mm to create a consistent external shell of the prosthesis and socket (Figure 2, iv). The steps of designing the finger prosthesis using MeshMixer are depicted in Figure 2. Finally, the data was prepared for printing by reorienting the prosthesis to sit vertically with the fingertip pointing upwards. The "make solid" tool was used to make sure the data was properly fused and did not have thickness issues. The bottom-most part was also extruded to a flat end to sit flat on the horizontal plane.

**B. DESIGN**

The mechanical stiffness of the fingertips is critical for dexterous manipulation of objects and tools [12]. To simulate the low stiffness of the fingertip we developed a technique:

* Asking the recipient to space their fingers slightly can help reduce the occlusions between the fingers.
* Wrapping the recipient’s forearm with a brown paper material serves as a good anchor for the scanning software to maintain proper tracking.
* Any occlusions between the fingers that can be fixed in pre-processing can usually be ignored.
to print the fingertip and the rest of the finger prosthesis at different infill values, thus resulting in different stiffness at the fingertip and the rest of the finger prosthesis. For this purpose, an additional step of the design stage is to split the finger model into tip and base sections as illustrated in figure 4(a) using the "Plane Cut" tool in MeshMixer.

C. PRINTING

The printing process depends on the printing material. In this work, we used a flexible thermoplastic polyurethane (TPU) filament from NinjaTek called NinjaFlex [15]. This material has a shore hardness of 85A. The resulting elasticity of the printed prostheses will depend on the printing thickness, type and level of infill, and temperature parameters since they determine the print density and layer adhesion. This material is not expected to pose any hazards to the human skin in normal use in the solid form [16].

The printer used in this work was a Replicator 2X (MakerBot Industries, LLC.). This printer uses a direct feed system for the filament which makes it suitable for use with flexible filaments. However, the extruder drive block was updated with an alternative extruder specialized for flexible filaments for better printing quality [17]. The files were prepared for printing using Simplify3D v 4.1.2 (Simplify3D, LLC.).

1) Printing: Soft Fingertips

Each finger consisted of two parts, the fingertip part, and the base part. The parts were imported to the 3D printer software and aligned properly. The used software, Simplify3D, supports printing multiple processes at the same time. A process is a set of printing parameters assigned to a subgroup of the parts that are being printed. In this case, we created two processes, one for the base parts, and one for the fingertip parts (Figure 4, b). The difference between the two processes is the infill percentage which was set to 90% for the base, and 10% for the fingertips (Figure 4, c). The base infill of 90% provides a rigid structure for the prosthesis to support the interaction force with the grasped object, similar to the function of bones in biological fingers. The fingertip infill of 10% provides the needed compliance at the fingertip to improve the interaction quality with the object, similar to the function of tissues in biological fingers.

2) Printing: Socket

The socket of the finger prosthesis is fused with the body of the prosthesis by design. The part of the body that serves as a socket is only extruded in one direction with 0.8 mm. This in printing results in only two shells without any infill between them, thus it is not affected by the infill level of the base part. Since the socket is a thin sheet of the TPU filament, the result is soft enough to comply with the contour of the stump.

3) Post-processing:

After printing the socket contour was trimmed, and the internal surface of the socket was smoothed using sandpaper. Artificial fingernails were glued on each finger to resemble a natural nail. Thin friction finger cots were added to the fingertips to improve the friction coefficient of the surface material in order to maintain a good grip on grasped objects.

III. EXPERIMENTS

A. 3D PRINTED TPU PARTS STIFFNESS

The proposed design of prosthetic fingers depends on the infill level on the fingertip to achieve a similar stiffness level to the biological fingertips. Previous research has shown the fingertip tissue stiffness to be in the range of 0 - 3 N/mm depending on the displacement and the contact angle between the fingertip and the measuring instrument [12]. The measured force on the fingertip was between 0 - 7 N for displacements between 0.5 - 3mm. To achieve similar stiffness we investigated the stiffness achieved with different levels of infill when printing with the TPU filament. The TPU filament used in this research has a Shore A hardness of 85 (NinjaFlex TPU). We printed cubes of 5cm dimensions at 10%, 20%, and 30% infill. We investigated two infill patterns in this research: grid infill and fast honeycomb infill, since these are commonly used patterns of infill, and they provide symmetrical structural integrity, and thus stiffness, in the plane of printing. However, stiffness in directions other than the printing plane will vary. We tested the stiffness of the test cubes in two directions; perpendicular to the printing plane, and horizontal to the printing plane. These are illustrated in Fig. 6 as vertical loading and lateral loading. To measure the stiffness of the test cubes we used a motorized force measurement stand (IMADA MX2-2500N-FA) equipped with a force measurement probe (ZTA-50N) and a linear encoder to measure force and displacement. The experimental setup is shown in Fig. 5. The measurement was performed by compressing the cubes vertically and then retracting for a stroke of 30 mm. The recorded data was then processed in

FIGURE 5: Force measurement stand used to measure the stiffness of the test cubes and the prosthesis fingertip. (shown in the figure as Finger prosthesis sample.)
MATLAB (MathWorks, Inc.) to plot the force and stiffness curves for each of the measurements.

Results
The force and stiffness measurements of the test cubes are shown in Fig. 6. The results showed, as expected, incremental force and stiffness profiles from the incremental infill levels for both infill types. The force and stiffness profiles were similar for the grid infill and the honeycomb infill in matching loading conditions. The measured force and stiffness in the lateral direction (horizontal to the printing plane) was significantly smaller than those in the vertical direction (perpendicular to the printing plane). This is because compression in the vertical direction causes the printed layers to compress against each other, while compression in the lateral direction compresses the cavities created by the infill structure.

B. 3D PRINTED FINGERTIP STIFFNESS
The force and stiffness measurements of the test cubes are shown in Fig. 6. The results showed, as expected, incremental force and stiffness profiles from the incremental infill levels for both infill types. The force and stiffness profiles were similar for the grid infill and the honeycomb infill in matching loading conditions. The measured force and stiffness in the lateral direction (horizontal to the printing plane) were significantly smaller than those in the vertical direction (perpendicular to the printing plane). This is because compression in the vertical direction causes the printed layers to compress against each other, while compression in the lateral direction compresses the cavities created by the infill structure.

Results
The force and stiffness measurements of the prosthetic finger fingertips are shown in Fig. 7. The results showed incremental force-displacement profiles with incremental infill levels, and corresponding incremental stiffness levels. The profiles of the stiffness-displacement measurements are different from those reported by Han and Kawamura [12] for biological fingers. However, the infill level of 10% showed 2 N/mm at 3 mm of deflection, similar to that of healthy persons at 15 degrees engagement angle.

C. CASE STUDIES
1) Participants
Two patients were enrolled in this study. Case 1 was a 55-year-old male, who was injured due to a firecracker incident. He had a partial amputation of the thumb, index, and middle fingers of the dominant right hand. Case 2 was an 86-year-old male, who had lost his middle and ring finger of the dominant right hand on an electric saw. The experiments were approved by the Internal Review Board of the University of Tsukuba Hospital (H27-071).

FIGURE 6: Results of force and stiffness measurements of the test cubes. Left: Force-Displacement, Middle: Stiffness-displacement, Right: infill type and loading direction.

FIGURE 7: Results of force and stiffness measurements of the fingertip of the prostheses.
2) Clinical Evaluation

Adaptation of the fabricated prostheses was confirmed by a physiatrist. Skin troubles including redness, swelling, and pigmentation were also checked. Clinical assessments were conducted using the Action Research Arm Test (ARAT) [18] with and without the fabricated prostheses. The ARAT is among the most widely used standardized measures for the upper limbs; it is efficient and can assess both the arm and the hand during the execution of functional tasks. It contains the assessment of four groups of motion (grasp, grip, pinch, and gross movements). The basic activities of daily life (BADL) and instrumental activities of daily life (IADL) were also evaluated for each participant.

3) Case 1

Case 1 was a 55-year-old male, who was injured due to a firecracker incident. He fractured the distal phalanx of his right thumb and the distal phalanxes and interphalangeal joints of the index and middle fingers. He underwent the trans-medial phalanx amputation of the index and middle fingers and trans-distal phalanx amputation of the thumb in an emergency operation on the same day. He had difficulties in his IADL and had severe pain in the tip of the amputated thumb when contacting a rigid surface or a rigid object.

This person’s occupation requires using a computer and making presentations; thus, his main complaint was the difficulty in typing on a keyboard. We fabricated a prosthesis for each of the thumb, index, and middle fingers. The first iteration was with the fingers fully extended and without soft fingertips, which was not satisfying for the recipient. He cited that fingers are slightly bent while typing on a keyboard, and that lack of softness on the fingertips makes it difficult to contact the keys in a stable manner. Thus, we fabricated a second iteration with soft fingertips, and with the distal joints bent roughly 20 on each of the prosthetic fingers. The second version met the recipient’s expectations well.

For evaluation, we used the ARAT scale with and without the fabricated prostheses and measured the typing speed on a computer with and without the designed prostheses. The ARAT scores are shown in Table 2, and a snapshot of the ARAT test is shown in figure 8. The typing speed results are shown in Table 1.

4) Case 2

Case 2 was an 86-year-old male, who was injured while using an electric saw. His distal and middle phalanxes of the middle and ring fingers were amputated. In addition, his little finger extensor was also ruptured. The injured extensor was sutured on the same day; however, loss of the 5th finger’s extension and flexion strength persisted. The proximal phalanxes of the middle and ring fingers were also fused during the operation.

This person cited complaints were: difficulty in holding a cup full of liquid, inability to use chopsticks during a meal, and inability to use a pen for handwriting.

We designed two prostheses to address this user’s complaints, one with slightly flexed fingers, and one with significantly flexed fingers (Figure 9). Since the proximal phalanxes of the middle and ring fingers are fused, the socket part in the designed prosthesis was also fused in the design process, with the two fingers separating from the middle phalanx. A harness made of palmar and dorsal fabric straps and Velcro tape extending from the prostheses to a wrist band was also designed for suspension.

To be able to hold a cup in his hand the distal and middle joints of the designed prosthesis were bent inwards roughly 30 each. This created a posture suitable for holding cylindrical objects. The fingers also flexed with the stump’s flexion, but the stump’s range of motion for this user was severely limited. As for holding chopsticks, we further flexed...
the finger’s proximal and distal joints to be able to use them as support for the chopsticks. The chopsticks used are specialized for persons with hand impairments; commonly used in Japan during and after physical therapy (Figure 1).

With the slightly-flexed fingers prosthesis (Figure 9, b) the recipient was able to hold a cup full of liquid successfully, and also was able put his little finger under the cup to support its weight, thanks to the additional grip provided by the prosthesis.

With the flexed fingers prosthesis (Figure 9, c) the user was able to hold the specialized chopsticks and operate them using his thumb and index fingers, while the prosthesis served as support to the chopsticks. The user was also able to hold a pen with this prosthesis and write his name in Chinese characters.

The ARAT scores of this user were obtained with the slightly flexed version of the prosthesis, and they are shown in Table 2, and a snapshot of the ARAT test is shown in figure 8 (right).

### IV. DISCUSSIONS

#### A. COMPARISON TO RELATED WORKS

The method proposed by Cabibihan J.J. [11] used CT images of the region of the affected fingers and the nonaffected fingers to design the socket and finger mould. This enabled remote collaboration to produce the finger prosthesis and reduced the time to acquire a prosthesis to less than a week. The method proposed in this work takes a similar approach by utilizing the image/scan data of the nonaffected fingers to design the shape of the finger prosthesis. The method devised in this work can reduce the required time to acquire a finger prosthesis to one day by utilizing 3D scanning instead of CT, and can also produce the soft fingertips by utilizing 3D printing.

Artificial finger prostheses are commonly fabricated for aesthetic purposes to conceal the amputation [19], therefore only aesthetic outcomes and user impressions are reported in passive and non-articulated finger prostheses research [11, 20], while functional measures are used in body-powered or articulated prostheses research [10, 9]. Therefore we opted to evaluate the case of using the prosthesis against not using the prosthesis.

### B. PRINTING TIME

The process of scanning, designing, and printing the prosthesis in one work day. The breakdown of each sub task for case 1 recipient was as follows:

- **Scanning:** 1 hour.
- **Pre-processing the scan data:** 1 hour.
- **Design:** 3 hours.
- **Printing:** 4.5 hours (roughly 1.5 hours for each finger).
- **Post-processing:** 1 hour.

It is important to note that these times are estimated after the process has been refined, and the data processing times are by a designer accustomed to the process and the software. In comparison, the method proposed by Cabibihan J-J was reported to require “less than one-week” [11]. The legacy method of prosthetic finger fabrication requires several appointments with the doctors, molding, and fitting procedures before the prostheses can be obtained. Thus, the waiting time can take up to 3 months [21].

### C. FABRICATION

The method of making soft fingertips can be improved further by investigating different infill levels, patterns, extrusion width, and layer heights. In this work, printing was done at 0.4mm extrusion width using a 0.4mm nozzle. Printing at lower extrusion widths was not possible with the current setup, however, smaller extrusion widths could be achievable with an improved extrusion method. Further, infill levels lower than 10% were not investigated in this work, since the vacancies in the fingertips that can be used for infill are small, infill levels lower than 10% would result in a lack of support in the structure. With lower extrusion width better support structures could be achieved by increasing the infill percentage without compromising the achieved stiffness.

Besides the produced stiffness at a given deflection, the stiffness-displacement profile should optimally be similar to the biological fingertips. Measuring the fingertip stiffness of biological fingertip is not possible with the current setup due to safety concerns. Han and Kawamura [12] measured the fingertip stiffness at approach angles of 15°, 30°, 45°, and 60°. Their results showed stiffness between 0-0.25 N/mm at 1mm displacement, 0.4-1.25 N/mm at 2mm displacement, and 1.5-3 N/mm at 3mm displacement. The stiffness obtained...
with the soft fingertips fabricated in this work was 2 N/mm between 1.5 and 4 mm. Stiffness at displacements less than 1.5 mm due to the outer shell’s stiffness which is higher than the epidermis of biological fingers. The current work used a TPU with 85A shore hardness filament with an FDM printer. Flexible filaments with lower shore hardness (FilaFlex TPE UltraSoft 70A) are available in the market, however, printing the softer filament is more challenging with desktop-sized printers, which will limit the adoption of the proposed method that is designed to be replicable with commonly available devices.

Han and Kawamura’s results also showed that fingertip’s made with silicone gel can produce a similar stiffness profile to the human fingertip tissue, rather than silicon rubber. In this work we used TPU filament which is similar to rubber material, producing a stiffness profile deviated from that of biological fingers. Modern bioprinters could be used to print the finger prostheses with silicon or biomaterials, which will help create a more 'human-like' prosthesis in appearance and mechanical properties.

The process of designing the prostheses requires a CAD designer to create the design of the prostheses as in Section II-B. The easier deployment will require creating software that automatically, or semi-automatically, generates the design of the prostheses from the scan data.

D. CASE STUDIES
The fitting is crucial when prescribing a finger prosthesis. Many cases have skin trouble or sensory disorders in the residual stump. Case 1 had severe pain at the tip of the residual thumb; therefore, he had difficulty touching objects or surfaces with his thumb. Using the novel finger prosthesis reduced his pain by protecting the fingertip and enhancing his ADL.

The ARAT score for the right hand was improved with the developed prosthesis. The task that this user could not accomplish without the prosthesis was picking up the ball bearing. The user cited that he could not pick up the ball bearing without the prostheses because of the stump’s stiffness, length, and shape. With the prosthesis and the soft fingertips, this task was completed successfully. The marble task was also slightly challenging without the prosthesis but was correctly achieved in both conditions.

The typing speed and accuracy were slightly improved with the prostheses. The user reported that the typing comfort was greatly improved with the prostheses due to the lower fingertip stiffness, and the proper finger length. He also reported that without the prostheses he only uses the ring finger on the right hand while typing, but with the prostheses, he could use all fingers, albeit slower than normal.

Adequate prosthesis fitting and training also have psychological benefits for the recipients [1]. Although the functional improvement in clinical measures can be limited, especially for a highly functional recipient like the case 1 user, task-specific improvements and the aesthetic appearance will improve the recipient’s social interaction and quality of life.

Case 1 user reported that he is much more comfortable using a computer and presenting in front of colleagues with the prosthesis.

One complaint the user cited was inadequate suspension on the index finger due to the conical shape of its stump. He used a strap of silicone finger cot to maintain good suspension on the index prosthesis. Better suspension should be addressed in future iterations of this prosthesis.

Fitting of the prosthesis on user 2 was possible with a simple harness made of cloth straps and Velcro tape. The user reported improved grip on a cup with the slightly flexed version of the prosthesis. This user has intact thumb and index fingers; thus, he could achieve most pinch grasps successfully. The tasks in which he struggled were holding a tool or cylindrical object that requires good grip force or multi-finger manipulation. In this regard, the slightly flexed and the flexed versions of this prosthesis achieved their intended purposes, respectively. The prosthesis offers additional contact points to hold the object (the cup) or serves as a support to free the thumb and index fingers to manipulate the object (the chopsticks and the pen) (Figure 1).

The ARAT scores for user 2 were identical with and without the prosthesis. The breakdown of the scores on the right hand is as follows: Grasp 15/18, Grip 12/12, Pinch 3/18, and Gross motor 9/9. The breakdown of the scores was also identical with and without the prosthesis. This user had poor articulation on the metacarpal segments and limited pinch force, which are likely the reasons for the low score. The prothetic finger cannot strengthen the pinch power due to the short and fused-type stump, and it cannot compensate for the limited metacarpal articulation. However, training with the prosthesis might mitigate these limitations over time.

The two cases presented above provided some further insight into the design of finger prostheses with 3D printing technology.

- In the case of grip (case 2), the nail and soft fingertip adjustment is not necessary, but in the case of only distal phalanx loss, it was significant to the function of the prosthesis.

- Lower stiffness on the fingertips was achieved in the proposed method, but the surface texture and friction were inadequate. Thus, coating the printed fingers with a thin layer of silicone or using friction finger cot will be beneficial.

- Using skin color filament or painting the printed fingers with skin color pigment will improve the aesthetic of the printed fingers.

- Suspension of the printed fingers without a harness depends on the profile of the stump. For case 1 user in this study suspension of the thumb and middle fingers was good, but suspension for the index finger was inadequate due to the conical shape of its stump.

V. CONCLUSIONS
In the proposed method it was possible to rapidly fabricate passive finger prostheses with soft fingertips. The presented
method also enables adjusting the shape of the prosthesis to fit the users’ needs or the purpose of occupational therapy. In the future, silicon or bio-materials can be used with bioprinters, using a similar procedure to the one presented here, to achieve mechanical properties closer to the human biological fingers and fingertips. Further studies on object manipulation with and without soft fingertips with a large number of users will further clarify the need and benefits of emulating the biological fingertip properties in prosthetic fingers.

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ABBREVIATIONS
The following abbreviations are used in this manuscript:
- CAD: Computer aided design
- FDM: Fused Deposition Modeling
- TPU: Thermoplastic polyurethane
- ARAT: Action research arm test
- BADL: Basic activities of daily living
- IADL: Instrumental activities of daily living
- CT: Computer Tomography

References
[1] Zala Kuret et al. “Adjustment to finger amputation and silicone finger prosthesis use”. In: Disability and Rehabilitation 41 (Jan. 2018), pp. 1–6.
[2] Kazuya Mizuochi. “Epidemiology of Lower Limb Amputation”. In: The Japanese Journal of Rehabilitation Medicine 55 (May 2018). (Article in Japanese), pp. 372–377.
[3] Yogesh Kini et al. “Comprehensive Prosthetic Rehabilitation of a Patient with Partial Finger Amputations using Silicone Biomaterial: A Technical Note”. In: Prosthetics and orthotics international 34 (Dec. 2010), pp. 488–94.
[4] Manawar Ahmad et al. “Comprehensive Rehabilitation of Partially Amputated Index Finger with Silicone Prosthesis: A Case Report with 3 years of Follow Up”. In: The Journal of Indian Prosthodontic Society 14 (Jan. 2013).
[5] Pooja Asnani et al. “Rehabilitation of amputated thumb with a silicone prosthesis”. In: The Journal of Natural Science, Biology and Medicine 6 (Jan. 2015), pp. 275–277.
[6] Mokhtar Arazpour et al. “Design and fabrication of a finger prosthesis based on a new method of suspension”. In: Prosthetics and orthotics international 37 (Nov. 2012).
[7] Vikas Kamble et al. “Silicone finger prostheses for single finger partial amputations: Two case reports”. In: Indian Journal of Dentistry 5 (Aug. 2014).
[8] Jelle Kate, Gerwin Smit, and Paul Breedveld. “3D-printed upper limb prostheses: a review”. In: Disability and Rehabilitation: Assistive Technology 12 (Feb. 2017), pp. 1–15.
[9] Raghad Alturkistani et al. “Affordable passive 3D-printed prosthesis for persons with partial hand amputation”. In: Prosthetics and Orthotics International 44.2 (2020), pp. 92–98.
[10] Keaton Young, James Pierce, and Jorge Zuniaga. “Assessment of body-powered 3D printed partial finger prostheses: a case study”. In: 3D Printing in Medicine 5 (Dec. 2019).
[11] John-John Cabibihan. “Patient-Specific Prosthetic Fingers by Remote Collaboration–A Case Study”. In: PLOS ONE 6.5 (May 2011), pp. 1–6.
[12] Hyun-Yong Han and S. Kawamura. “Analysis of stiffness of human fingertip and comparison with artificial fingers”. In: IEEE SMC’99 Conference Proceedings. 1999 IEEE International Conference on Systems, Man, and Cybernetics (Cat. No.99CH37028), Vol. 2. 1999, 800–805 vol.2.
[13] Alireza Mohammadi et al. “A practical 3D-printed soft robotic prosthetic hand with multi-articulating capabilities”. In: PLOS ONE 15.5 (May 2020), pp. 1–23.
[14] Patricia Capsi Morales et al. “Comparison between rigid and soft poly-articulated prosthetic hands in non-expert myo-electric users shows advantages of soft robotics”. In: Scientific Reports 11 (Dec. 2021).
[15] “NinjaFlex 3D Printing Filament: Technical Specifications. Available online: https://ninjatek.com/wp-content/uploads/2019/10/NinjaFlex-TDS.pdf (accessed on 12 August 2020)”. In: ()
[16] “NinjaFlex 3D Printing Filament: Safety Data Sheet. Available online: http://ninjatek.com/wp-content/uploads/2019/09/SDS-NinjaFlex-rev1.pdf (accessed on 12 August 2020)”. In: ()
[17] “Flexion Extruder for Replicator-Style Printers. Available online: https://flexionextruder.com/support/dual-extruder-installation/ (accessed on 16 January 2022)”
[18] Nuray Yozbatiran, Lucy Der-Yeghiaian, and Steven C. Cramer. “A Standardized Approach to Performing the Action Research Arm Test”. In: Neurorehabilitation and Neural Repair 22.1 (2008), pp. 78–90.
[19] Zala Kuret et al. “Adjustment to finger amputation and silicone finger prosthesis use”. In: Disability and Rehabilitation 41 (2019), pp. 1307–1312.
[20] Shanmuganathan Natarajan et al. “Aesthetic Finger Prosthesis”. In: Journal of Indian Prosthodontic Society 11 (Dec. 2011), pp. 232–7.
[21] Barbra Almond. “Early and Temporary Use of Finger Prosthetics to Aid Rehabilitation”. In: Journal of hand therapy : official journal of the American Society of Hand Therapists 24 (Mar. 2011), pp. 62–5.
