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Fabrication of low cost soft tissue prostheses with the desktop 3D printer

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Soft tissue prostheses such as artificial ear, eye and nose are widely used in the maxillofacial rehabilitation. In this report we demonstrate how to fabricate soft prostheses mold with a low cost desktop 3D printer. The fabrication method used is referred to as Scanning Printing Polishing Casting (SPPC). Firstly the anatomy is scanned with a 3D scanner, then a tissue casting mold is designed on computer and printed with a desktop 3D printer. Subsequently, a chemical polishing method is used to polish the casting mold by removing the staircase effect and acquiring a smooth surface. Finally, the last step is to cast medical grade silicone into the mold. After the silicone is cured, the fine soft prostheses can be removed from the mold. Utilizing the SPPC method, soft prostheses with smooth surface and complicated structure can be fabricated at a low cost. Accordingly, the total cost of fabricating ear prosthesis is about $30, which is much lower than the current soft prostheses fabrication methods.

S oft tissue prostheses are widely used in maxillofacial rehabilitation. Patient numbers is ever increasing due to the advancements in medicine, surgical techniques and in particular cancer survival rates[1]. However, the high fabrication cost of traditional prostheses prompted the researchers to explore alternatives to reduce the cost and time of fabrication. Three-dimensional (3D) printing or rapid prototyping (RP) is a layered manufacturing method that can be used to fabricate complex structures. It is an additive manufacturing (AM) process, fundamentally different from the conventional subtractive manufacturing processes. Using 3D printing a physical object can be fabricated from a 3D computer-aided design (CAD) model layer by layer, more conveniently and more rapidly than other manufacturing means. Additionally, it is easy to customize a product according to personal requirement, consequently a wide variety of applications of 3D printing technology in soft matter fabrication have emerged recently[2–8]. The use of 3D printing can help in the development of omnibearing biodevices[4]. Such as described in the report by Wang et al.,[5], who used hydrogel and cells to fabricate models that mimic complex soft organs in vitro with the help of 3D printing. Also, Landers et al., printed a hydrogel scaffolds using 3D plotter to attain a designed external shape and a well-defined internal pore structure[6].

Many reports also discussed the fabrication of soft tissues for implant, and scaffolds with cell-seeded hydrogel or collagen matrix for clinical application were developed[9–12]. High-fidelity ears with collagen type I hydrogel scaffolds were fabricated by injection. Even following an extended period after implantation, they continue to effectively mimic the native auricle both biomechanically and histologically[10]. To improve the mechanical properties of the fibrous collagen matrix, composite ear scaffolds with wire frameworks were used to ensure a 3D shape after implantation[11]. Mannoor, M. S., et al[12] printed bionic ears able to gather inductively-coupled signals from cochlea-shaped electrodes, demonstrating the merging capabilities of biological and nanoelectronic functionalities. However, because scaffolds or soft tissues based on tissue engineering are designed to acquire real tissues after implanting, further clinical study and a thorough ethics evaluation are still needed.

Furthermore, in 2003 Cheah et al.,[13,14] integrated CAD/CAM techniques for developing facial prostheses and described a complete fabrication process using the selective laser sintering (SLS) 3D printing technology. It is worth noting, they and Eggbeer et al.[15] also discussed the difference between indirect mold production via silicone rubber molding and direct mold production via RP fabrication. In addition, a template-based framework was proposed to rebuild the nasal 3D model with the data from 3D and computed tomography (CT) scans[16]. The results showed that this method had advantages over other rebuilding methods in terms of accuracy, speed, safety and cost. E. Bassoli et al.,[17] reported a combined 3D printing/indirect replication method to fabricate 3D vascular-like structures of soft tissue[17]; using the ProJet® HD 3000 3D printer from 3D Systems Inc. to print the negative mold of the vascular structure.

A team from Italy led by De Crescenzio and Ciocca made a significant contribution to the facial rehabilitation field[18–20] when they reported a comprehensive solution to the design and fabrication of prosthesis. They created a real anatomic reference model library, namely the "Ear & Nose Digital Library", which can be very useful for the reconstruction of the facial defects. In addition, they described how the definitive acrylic ear cast mold was printed by ®Z Printer 310 (Z Corp, taken over by 3D system Inc. in 2012), which was then transformed into a wax ear with the vinyl polysiloxane material.

A team from UK led by Eggbeer and Bibb performed a long term and remarkable research to study how to apply digital technologies in maxillofacial prosthetics[1,15,21–25]. Eggbeer et al., compared the prostheses fabricated by 3D printing against a prosthesis made by conventional techniques[15]. In their nasal prosthesis case study, 3D printing enabled the prosthetics to work in a more flexible manner. However, they determined that the directly printed prosthesis has poor mechanical properties and untested biological responses, and suggested that the best way is to print the prosthesis mold and cure the prosthesis with silicone rubber. Worth mentioning, skin features such as wrinkles and texture in auricular and nasal prostheses have been successfully fabricated by 3D printing[1]. The time required for prosthesis fabrication by 3D printing was found to be considerable shorter than that required by the conventional methods.

As the prosthesis is personally customized, mass fabrication methods such as metallic mold casting or injection molding are typically not suitable. A conventional process for the construction of prostheses is particularly lengthy, as it includes many steps: impression, plaster replica, base plate fabrication, mold fabrication, mold packing, curing, and extrinsic finishing. The process is laborious and expensive in addition to time-consuming. The maxillofacial prosthodontist determines the correct size, shape, and position of the prosthesis for each individual patient, hand-sculpts an impression in wax, then casts the shape in silicone. A handmade silicone ear or nose costs up to $4000, and requires 5–7 hospital visits for customization. The process takes 5–10 weeks in total[26].

Many researchers have previously demonstrated 3D printing/RP technology as an effective way to accelerate the prostheses fabrication process and reduce its cost. The primary material used in prostheses, either silicon or Polydimethylsiloxane (PDMS), is more suited to casting. The so-called rapid tool, soft tool or bridge tool[27] fabricated by 3D printing is commonly used to cast prostheses. It should be noted, however, that the 3D printers used in this previous research were industrial-grade and therefore quite expensive. Indeed, the cost of fine prostheses mold-fabricated by an industrial 3D printer is still high, which has hindered the wider use of 3D printing. According to the quote given by Magicfirm, LLC. Hangzhou, China, the fabrication price is $2.2 per cm³ using the stereolithography apparatus (SLA) of a 3D printer, indicating a cost of $411.80 for an ear mold with a size of 7.8 × 5.0 × 4.8 cm. A prosthetic product fabricated by 3D printing from Fripp Design & Research in the UK costs around $4,000 each, almost as much as a handmade product[28]. If such prostheses could be manufactured at home, the cost would drop dramatically, greatly benefiting patients.

The desktop 3D printer (personal 3D printer), also known as the open source 3D printer, is very popular among the do it yourself (DIY) variants. The advantages of desktop 3D printer include low cost and as a result, many people can afford a small size printer with extremely low to zero toxicity and waste. With the expiration of the key patents of Fused Deposition Modeling (FDM), the technology used in desktop 3D printer, a large open-source development community has emerged, and a desktop 3D printer now only cost $200–$1000.

Two standard types of desktop 3D printer are the RepRap and the Fab@Home; however, everyone can change the desktop 3D printer design according to their requirements thanks to its open source development. At present the desktop 3D printer is being widely used in education, DIY manufacturing, research and industry. As illustrated by the successful production of micro- and milli-scale reactionware with a desktop 3D printer (3DTouch)[29].

The main task during the manufacture of soft prostheses is the making of the casting mold, which is also the main component of the cost incurred during the whole prostheses fabrication process. If the casting mold can be fabricated using a desktop 3D printer, and as such printers become readily affordable, then doctors could fabricate the prostheses in their offices, or the patients could do it at home. Nevertheless the staircase effect (contour like structure) caused by the layered manufacturing is a challenge which impedes the acquisition of smooth surface in 3D printing. This drawback is especially serious in the desktop 3D printer due to the layer thickness, as shown in Fig. 1.

In this study, we focus on how to apply the low cost desktop 3D printer to print the casting mold. The fabrication method used is called Scanning Printing Polishing Casting (SPPC). The key consideration when using SPPC is how to fabricate a negative casting mold with smooth surface inside, and will be addressed in this report. To that end, the polishing method, which can ensure that the surface quality of the mold is adequate to be used in the prostheses casting, was systematically investigated. Moreover, it is proven that the soft prostheses can be affordably manufactured, under $30 each, at home or in a personal lab setting without any expensive technical equipment. SPPC also can be widely used in the fabrication of soft muscle, hydrogel structure in tissue engineering, artificial skin, customized jewel, etc.

Methods

The typical process of SPPC is shown in Fig. 2. Firstly, 3D data for the prostheses are acquired with a 3D scanner. Once acquired, the datasets are used to generate a digital 3D model of the negative mold for casting by using a 3D modeling software such as 3D max, Rhinoceros, or SolidWorks, etc. Subsequently, the 3D model is converted into G code language by a slicing software tool, which can then be read by a desktop 3D printer. A common polymer filament, Acrylonitrile Butadiene Styrene copolymers (ABS), is applied for 3D printing. Since the multi-strip-like structure caused by 3D printing will affect the prostheses surface quality, acetone vapor is used to eliminate the layer thickness effect of the mold, as ABS is soluble in acetone. After polishing, silicone is poured into the mold. The soft prostheses can be easily pulled out/demolded from the mold because the solidified silicone provides extra strength and elasticity.

A Kinect depth sensor for Microsoft Windows was used to scan the original model, and its digital dataset was saved as a STL file[30]. The negative mold model was then designed using the Rhinoceros V4.0 software. The slice software Slic3r was used to generate G code files for the desktop 3D printer, RepGo X1, which was purchased from Xiangtan Dot Go 3D technology Corporation for about $570.

Silicone part A and part B (Dongguan Hongfeng Silicone Materials Co., LTD) were mixed in a 1 : 1 (weight: weight) ratio and stirred for 2 minutes, and then the mixture was degassed in a vacuum chamber for 10–15 minutes. ABS is a thermoplastic polymer material with high strength, good toughness and easy to machine. Nowadays it is widely used in FDM printing. However the poor surface finish quality has limited the development of 3D printing, in both appearance and performance. A simple polishing device has been assembled, as shown in Fig. 3. It includes a heater to
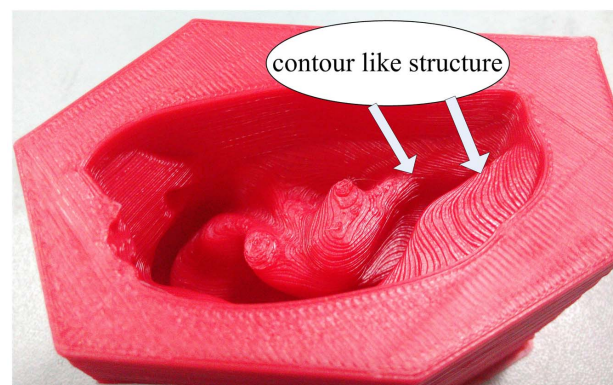

Figure 1 | Staircase behavior in 3D printing (Ear negative mold, layer height 0.3 mm, taken by the author, Guang-huai Xue).
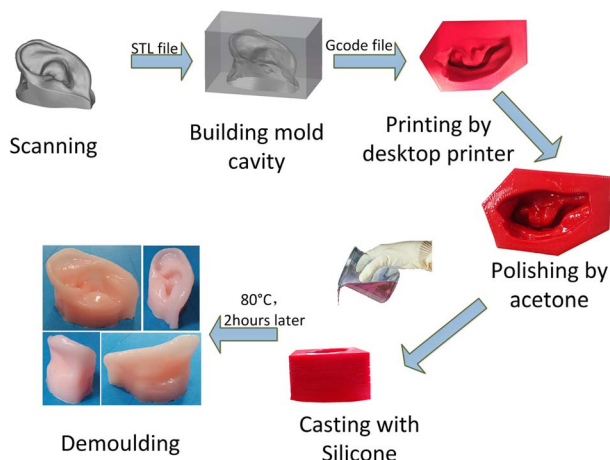
Figure 2 | Typical SPPC process (All photographs were taken by the author, Guang-huai Xue).

generate acetone vapor, a beaker to contain liquid acetone, a sealed container to control acetone vapor pressure, a temperature sensor to monitor polishing temperature, a support frame to fix ABS mold.

As shown in Fig. 4, when the heater is on, the beaker containing the acetone is heated to a temperature higher than boiling point of acetone (56.5°C) as it is set to 80°C for the experiment. Heated acetone vapor rises from beaker and washes the ABS sample. Since ABS is soluble in acetone, the surface of the mold is gradually dissolved. By the influence of gravity and liquid surface tension, the staircase surface slowly becomes smoothed. The longer the mold is polished, the more ABS is dissolved, which may affect the precision of the mold and its surface roughness. However acetone will no longer be evaporated when the pressure inside the sealed container reaches its saturated vapor pressure. A simple equation (State Equation of Ideal Gas) was used to calculate the reasonable acetone volume.

$$PV = \frac{m}{M}RT = \frac{\rho V_{acetone}}{M}RT \qquad (1)$$

Saturated vapor pressure of acetone in 80°C: P = 224 KPa, Volume of the sealed container $V = \frac{\pi}{4}d^2h = 1.445L$, Molecular weight of acetone M = 58, Scale factor $R = 8.31\ J/(mol \cdot K), T = 353\ K$, acetone density $\rho = 0.788\ g/cm^3$.

We can calculate $V_{acetone} = 8.12\ ml$, which means that the pressure of acetone in the sealed container reaches its saturated vapor pressure. So 10 ml acetone is added into beaker before every experiment to ensure there is enough acetone in the container when the mold is polished.
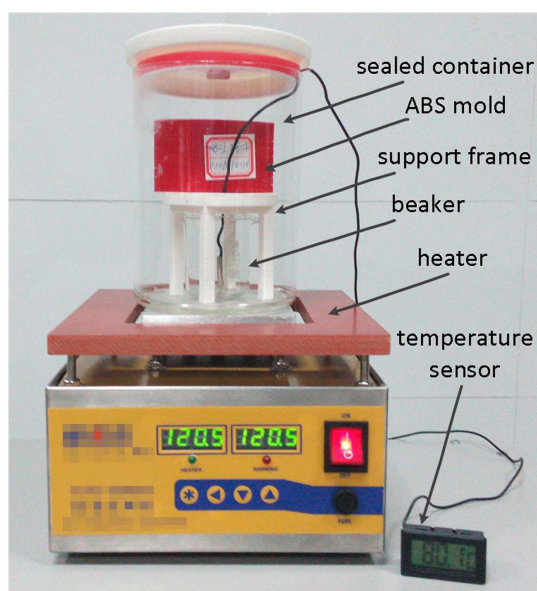

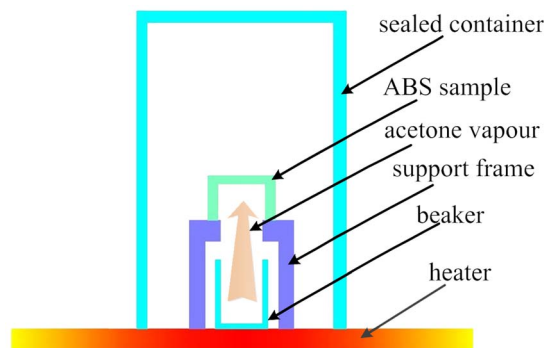**Figure 3 | Polishing device (Taken by the author, Guang-huai Xue).**

Figure 4 | Working principle of polishing device.

The surface quality of the ABS mold is influenced by many polishing parameters such as temperature, vapor pressure, layer height of 3D printing, polishing time and model structure. A box mold was chosen as a standard sample, shown in Fig. 5. Different layer-thickness ABS models were polished for different times to study how to achieve a better surface finish. The surface quality was assessed using an inductance type roughness tester, a SRT6200 (Guangzhou Landtek Instruments Co. Ltd. Guangzhou China), and a digital microscope (KEYENCE. SRT6200). The surface roughness tester can measure a surface with Ra 0.05 ~ 10.00 μm and Rz 0.020 ~ 100.0 μm and an accuracy of not more than ±5%.

Results and discussion

Polish process analysis. In order to study the polish effect in different parts of the mold, eight 0.2 mm layer-high samples were printed and polished for different times. Afterward they were taken out and allowed to dry out for about 1 hour. The polish process can be clearly revealed with the help of a digital microscope, as shown in Fig. 6. The wall of a sample is piled up with 0.2 mm high filaments (which Fig. 6 part a), while the bottom is lined up with 0.68 mm width filaments (which Fig. 6 part b). The polish effect is not obvious until the 6 minutes point. When enough ABS is dissolved, the grooves between adjacent filaments are filled and the boundaries of filaments become indistinguishable because of the gravity and liquid surface tension. Finally all boundaries disappear and a smooth surface is acquired at about the 12 minutes point. However, if the process is allowed to continue, extra ABS is dissolved which causes pits on the surface, and subsequently it randomly redeposit on the surface resulting in some peaks. These pits and peaks will damage the smooth surface and as a result surface roughness increases.

According to the analysis described above, the sample needs to be taken out from the sealed container in timely fashion for a smooth surface. Both the wall and bottom of sample seem to attain a rather low surface roughness at about 12 minutes. However a surface roughness tester is required for quantitative analysis.

Surface roughness is quantified by the vertical deviations of a real surface from its ideal form. It is usually characterized by the arith-
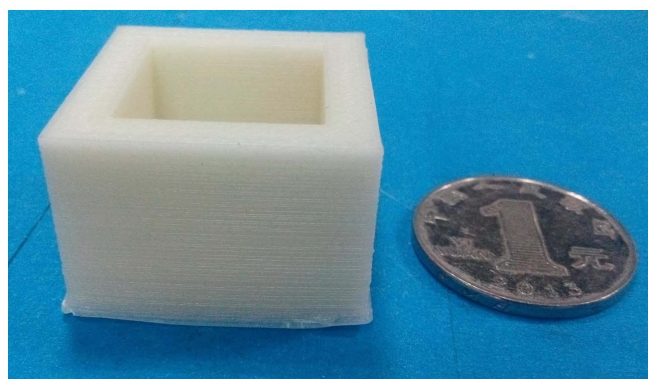

Figure 5 | Box mold (standard sample) for studying polishing effect (Taken by the author, Guang-huai Xue).
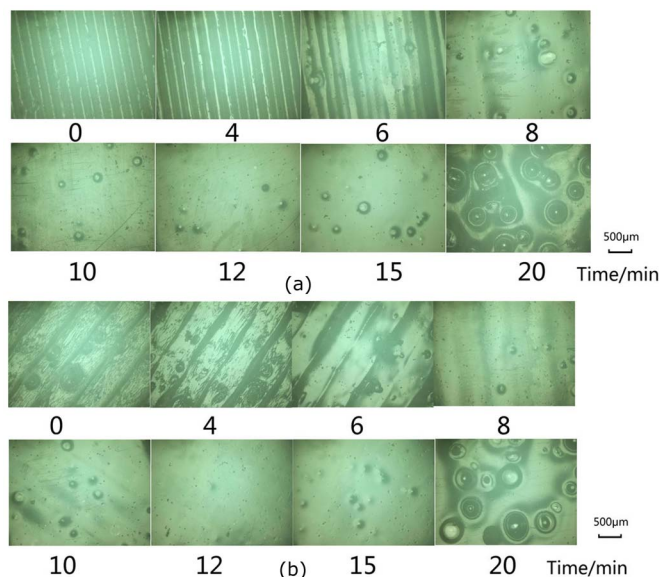
Figure 6 | Surface quality changing over time, 0.2 mm layer-high (a) sample wall, (b) sample bottom.

metical mean deviation of profile, Ra, and the maximum height of profile, Rz.

$$Ra = \frac{1}{n}\sum_{i=1}^{n}|y_i| \qquad (2)$$

Where y_i is the vertical distance from the mean line to the ith data point. $Rz = Rp - Rv$, maximum peek high $Rp = \max_i y_i$, maximum valley high $Rv = \min_i y_i$.

The surface roughness of the 0.2 mm layer-high samples polished for different times are measured and shown in Fig. 7. The polish curve is quite similar to what we can see under the digital microscope. It can been seen that the roughness of the sample from the bottom starts to drop dramatically at the beginning, likely as a result of the bottom being in a vertical position relative to the direction of the acetone vapor and thus totally exposed to the vapor. The sample from the wall is horizontal to the vapor and its polish effect is not obvious until the 6 minutes point. ABS surface can be smoothed by
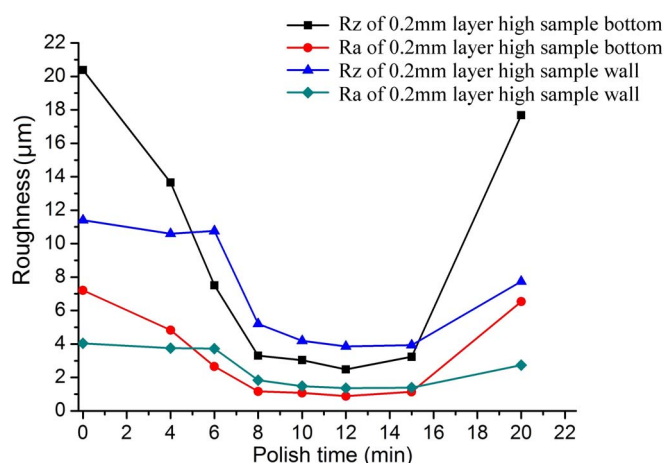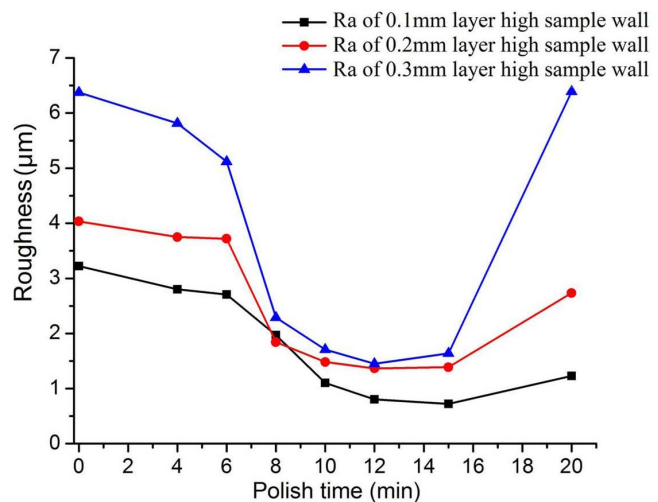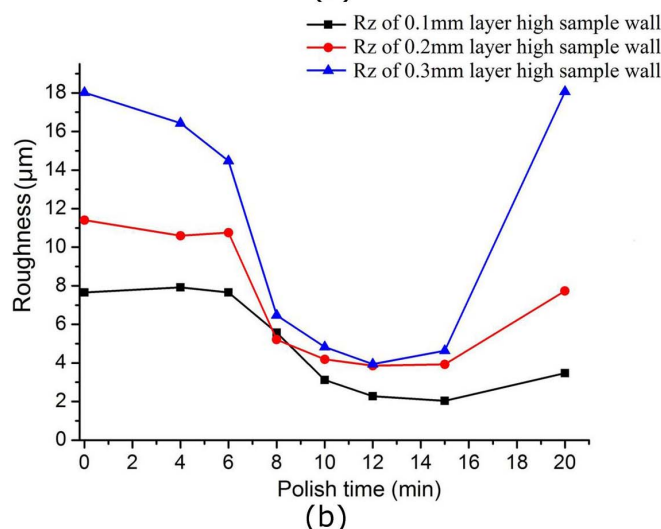

Figure 7 | Surface roughness of 0.2 mm layer-high samples change over polish time.

Figure 8 | Surface roughness of different layer high samples change over polish time, (a) Ra, (b) Rz.

polishing with a 1.0 μm Ra, which rivals the glossy smooth surface achieved by finish tuning or accurate grinding with traditional machine. Surface roughness increases at 20 minutes as extra ABS is dissolved resulting in pits and peaks.

Samples of 0.1 mm, 0.2 mm and 0.3 mm layer height were printed and polished to study the relationship between the layer height and the polishing effect. The roughness of samples walls were measured and are shown in Fig. 8. Generally speaking, the higher the sample layer height is, the bigger surface roughness will be. However all layer height samples attain their finest smooth surface at about 12–15 minutes. The sample of 0.1 mm layer height from the wall can be polished to a surface as smooth as 0.8 μm.

The ear mold is structurally much more complex than these samples. Several molds of 0.2 mm layer height were printed and polished for different times. The staircase effect is very clear when the mold is unpolished, as shown in Fig. 9a. A smooth surface can be acquired at about 15 minutes, as shown in Fig. 9b. For better assessment of the polishing effect, both polished and unpolished ear molds were cast with translucent silicone. Silicone ear prosthesis cast in unpolished mold is full of streaks on its surface, making it look coarse and opaque to light, Fig. 9c. However, when the staircase effect on the surface of ear mold is eliminated, the ear prosthesis looks much smoother and more transparent, Fig. 9d, and the fine soft ear with skin color is shown in Fig. 9e.

Table 1 | The fabrication cost of silicone ear with SPPC method for first timers

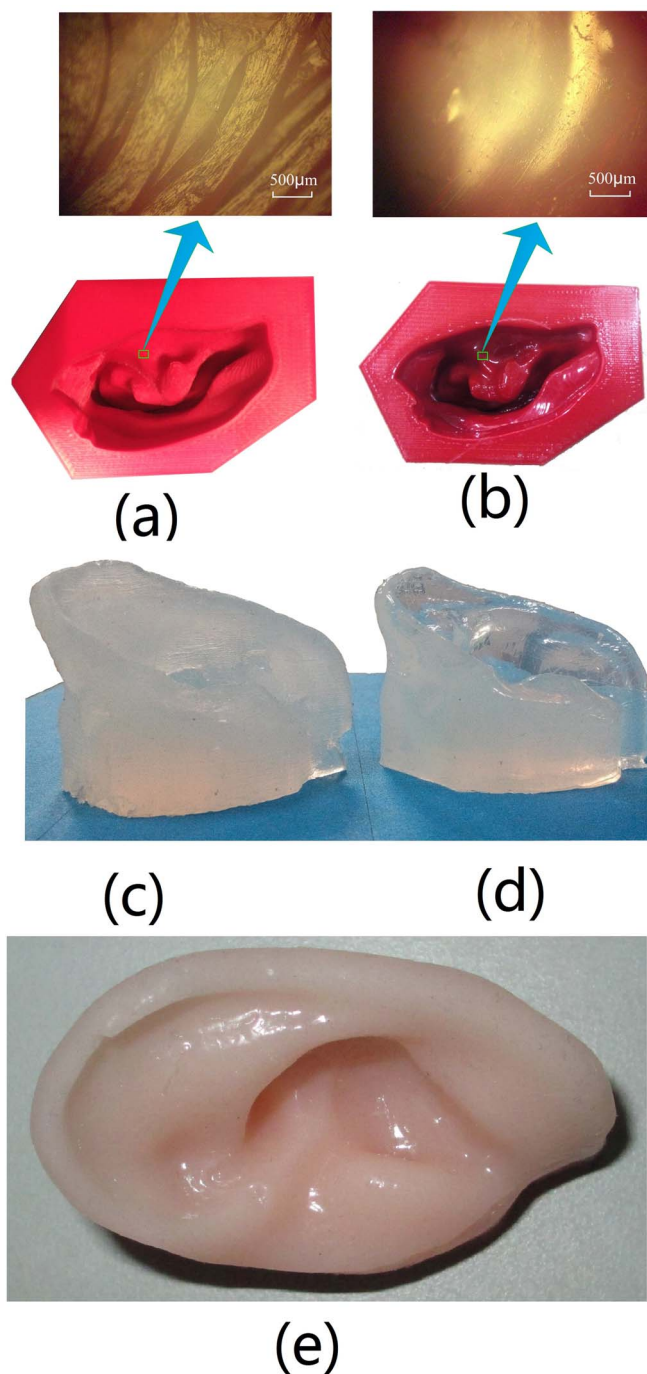| Item	Amount	Cost
Silicone	23.7 g	$1.2
ABS	63.5 g	$0.8
Acetone	10 ml	$0.1
Sealed Container	1	$2.5
Power Consumption	≈1 kW·h	$0.5
Labor cost	2 h	$20
Others (machine wear, beaker, etc.)	–	$4
Total cost		$29.1

Figure 9 | Silicone ear (a) Unpolished mold (b) Polished mold (c) Ear casted with unpolished mold (d) Ear casted with polished mold (e) fine silicone ear (All photographs were taken by the author, Guang-huai Xue).

Cost analysis. The biggest merit of the SPPC method is low cost, the mold fabrication cost could be negligible, as it is printed by a desktop 3D printer and it can be reused many times. The materials, reagents and apparatus used in the mold fabrication and casting of the prosthesis are cheap and readily available. As shown in Tab. 1, the fabrication cost of the first silicone ear can be as low as $29.1. After the mold is printed and polished, fabricating the next prosthesis will only require 23.7 g silicone, 10 min of labor cost and additional minor costs incurred for machinery ownership, operation wear and tear; which means that the final cost is less than $5.

The material most commonly used to fabricate prostheses is silicon, considering its long-term stability, strength and softness. A comparative analysis of 3D-printed prostheses fabrication using a variety of materials is shown in Tab. 2. Silicon solidifies slowly, so fabricating silicon prostheses by direct writing is not favorable; however, silicon can be fabricated effectively by bioprinter. Maxillofacial rehabilitation is not the most suitable research area for bioprinted tissue engineering, currently, though scaffold fabricated by bioprinter is quite promising. Mold-casting prostheses is most preferable.

Almost all commercial 3D printers, including the SLA, inkjet, and SLS, can print a casting mold with a variety of materials. Basically, SLA and SLS printers have a high resolution and can fabricate a mold with a surface roughness less than 10 μm, but they are very expensive – sometimes more than $200,000. Inkjet 3D printers print using gypsum powder, which decreases cost but requires further process after printing. Compared to other methods, SPPC dramatically drops costs and creates products with fine surface quality.

Mechanical performance. The mechanical and physical properties of silicone prostheses made by SPPC are shown in Tab. 3. Compared to the properties of a range of other commercially-available silicone rubber maxillofacial materials[31], this silicone prosthesis possesses considerable advantages in its tensile strength and tear strength. Its elongation percentage rivals that of other commercial materials, its hardness ranges from 0 to 60 A°, and its heat resistance is above 200°C, all of which meet the general requirements of prosthetic products.

Parting fabrication. Fabricating an ear prosthesis is much simpler than fabricating a hand prosthesis, as only one mold is required. The prosthesis can be easily pulled out of the ear mold, due to the structure of the ear, and the high elasticity and low hardness of silicone. Two or more part molds are necessary, however, when an ear prosthesis with low elasticity and high hardness is needed. It is impossible to cast a silicone hand with only one mold. Upper and lower molds are designed and printed, then tightened by bolts, as shown in Fig. 10. A hand prosthesis looks much like a real human hand in shape and color; nevertheless, it requires much further process and refinement for detail, such as hair and varying texture. Technically speaking, any shape of silicone prosthesis can be cast by parting fabrication.

Conclusion

As a desktop 3D printer is very cheap, it is also referred to as a personal 3D printer and it will become as popular and common as the personal computer, this means that almost everyone can afford and use their desktop 3D printer to print whatever they want. It is every interesting and creative to develop research applications with a desktop 3D printer.

In this study we aimed to fabricate the soft prostheses with the help of a desktop 3D printer and succeeded in attaining this goal. The printing costs of negative mold were negligible when compared to the traditional methods. In this report, a cheap and convenient method (SPPC) of fabricating silicone prosthesis is demonstrated. The staircase effect of the mold caused by the desktop 3D printer is eliminated

Table 2 | Comparative analysis of prostheses fabrication with 3D printing

3D printer	Material Used	Cost	Surface roughness	Fabricating method
SLA	Ultraviolet resin	Expensive	High	Mold Casting
SLS	Powder	Expensive	High	Mold Casting
Inkjet	Gypsum powder	Middle	Middle	Mold Casting
Bioprinter	Hydrogel	Middle	High	Direct Writing
SPPC	Polymer silk	Cheap	Low	Mold Casting

Table 3 | Mechanical properties of prostheses

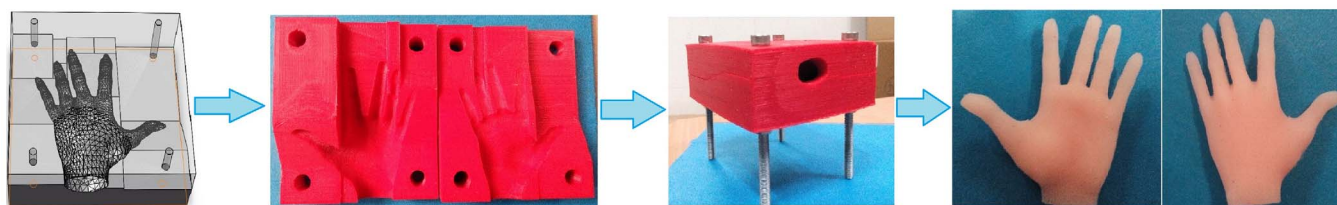|	Density (g/cm^3)	Viscosity (kPa.s)	Percentage Elongation(%)	Tear Strength(kN/m)	Tensile Strength(kN/m)	Hardness (A$^\circ$)	Heat Resistance($^\circ$C)
Value	1.12	10	450	27	10	0 ~ 60	200 ~ 300

Figure 10 | Parting fabricating of hand prosthesis (All photographs were taken by the author, Guang-huai Xue).

to produce a prosthesis with smooth surface. Furthermore, prosthesis fabrication is not limited by its shape, which promises a prosperous future for the application of SPPC. Not only for prostheses, but also masks, cosmetic products, sex products, etc., which need to be personally customized, can be fabricated with a desktop 3D printer in the near future.

1. Bibb, R., Eggbeer, D. & Evans, P. Rapid prototyping technologies in soft tissue facial prosthetics: current state of the art. *Rapid Prototyping J.* **16**, 130–137 (2010).
2. Yeong, W. Y., Chua, C. K., Leong, K. F. & Chandrasekaran, M. Rapid prototyping in tissue engineering: challenges and potential. *Trends Biotechnol.* **22**, 643–652 (2004).
3. Billiet, T., Vandenhaute, M., Schelfhout, J., Vlierberghe, S. V. & Dubruel, P. A review of trends and limitations in hydrogel-rapid prototyping for tissue engineering. *Biomater.* **33**, 6020–6041 (2012).
4. Lantada, A. D. & Morgado, P. L. Rapid prototyping for biomedical engineering: current capabilities and challenges. *Annu. Rev. bioeng.* **14**, 73–96 (2012).
5. Wang, X. H., Yan, Y. N. & Zhang, R. J. Recent trends and challenges in complex organ manufacturing. *Tissue Eng. Part B* **16**, 189–197 (2010).
6. Landers, R., Hübner, U., Schmelzeisen, R. & Mülhaupt, R. Rapid prototyping of scaffolds derived from thermoreversible hydrogels and tailored for applications in tissue engineering. *Biomater.* **23**, 4437–4447 (2002).
7. Yang, S., Leong, K. F., Du, Z. & Chua, C. K. The design of scaffolds for use in tissue engineering. Part II. Rapid prototyping techniques. *Tissue Eng.* **8**, 1–11 (2002).
8. Dhariwala, B., Hunt, E. & Boland, T. Rapid prototyping of tissue-engineering constructs, using photopolymerizable hydrogels and stereolithography. *Tissue Eng.* **10**, 1316–1322 (2004).
9. Raghunath, J., Rollo, J., Sales, K. M., Butler, P. E., & Seifalian, A. M. Biomaterials and scaffold design: key to tissue-engineering cartilage. *Biotech. Appl. Biochem.* **46**, 73–84 (2007).
10. Reiffel, A. J. *et al.* High-fidelity tissue engineering of patient-specific auricles for reconstruction of pediatric microtia and other auricular deformities. *PloS one* **8**, e56506 (2013).
11. Cervantes, T. M. *et al.* Design of composite scaffolds and three-dimensional shape analysis for tissue-engineered ear. *J. R. Soc. Interface* **10**, 20130413 (2013).
12. Mannoor, M. S. *et al.* 3D printed bionic ears. *Nano lett.* **13**, 2634–2639 (2013).
13. Cheah, C. M., Chua, C. K., Tan, K. H. & Teo, C. K. Integration of laser surface digitizing with CAD/CAM techniques for developing facial prostheses. Part 1: Design and fabrication of prosthesis replicas. *Int. J. Prosthodont.* **16**, 435–441 (2002).
14. Cheah, C. M., Chua, C. K. & Tan, K. H. Integration of laser surface digitizing with CAD/CAM techniques for developing facial prostheses. Part 2: Development of molding techniques for casting prosthetic parts. *Int. J. Prosthodont.* **16**, 543–548 (2002).
15. Eggbeer, D., Bibb, R., Evans, P. & Ji, L. Evaluation of direct and indirect additive manufacture of maxillofacial prostheses. *P. I. Mech. Eng. H.* **226**, 718–728 (2012).
16. Sun, J., Chen, X., Liao, H. & Xi, J. Template-based framework for nasal prosthesis fabrication. *Rapid Prototyping J.* **19**, 68–76 (2013).
17. Bassoli, E. *et al.* A combined additive layer manufacturing/indirect replication method to prototype 3D vascular-like structures of soft tissue and endocrine organs. *Virtual Phys. Prototyping* **7**, 3–11 (2012).
18. De Crescenzio, F., Fantini, M., Ciocca, L., Persiani, F. & Scotti, R. Design and manufacturing of ear prosthesis by means of rapid prototyping technology. *P. I. Mech. Eng. H.* **225**, 296–302 (2011).
19. Ciocca, L. & Scotti, R. CAD-CAM generated ear cast by means of a laser scanner and rapid prototyping machine. *J. Prosthet. Dent.* **92**, 591–595 (2004).
20. Fantini, M., De Crescenzio, F. & Ciocca, L. Design and Rapid Manufacturing of anatomical prosthesis for facial rehabilitation. *Int. J. Interact. Des. Manuf.* **7**, 51–62 (2013).
21. Eggbeer, D., Evans, P. L. & Bibb, R. A pilot study in the application of texture relief for digitally designed facial prostheses. *P. I. Mech. Eng. H.* **220**, 705–714 (2006).
22. Evans, P., Eggbeer, D. & Bibb, R. Orbital prosthesis wax pattern production using computer aided design and rapid prototyping techniques. *J. Maxillofac. Prosthet. Tech.* **7**, 11–15 (2004).
23. Eggbeer, D., Bibb, R. & Evans, P. Assessment of digital technologies in the design of a magnetic retained auricular prosthesis. *J. Maxillofac. Prosthet. Tech.* **9**, 1–4 (2006).
24. Eggbeer, D., Bibb, R. & Evans, P. Toward identifying specification requirements for digital bone-anchored prosthesis design incorporating substructure fabrication: a pilot study. *Int. J. Prosthodont.* **19**, 258–263 (2005).
25. Eggbeer, D., Evans, P. L. & Bibb, R. A pilot study in the application of texture relief for digitally designed facial prostheses. *P. I. Mech. Eng. H.* **220**, 705–714 (2006).
26. Jeffery, C. M. Facial Prostheses, http://www.maxillofacialprosthetics.org/patients/patiented_fp.html#userconsent#, (2014) (Date of access: 13/08/2014).
27. Ferreira, J. C. & Mateus, A. Studies of rapid soft tooling with conformal cooling channels for plastic injection moulding. *Journal of Mater. Process. Tech.* **142**, 508–516 (2003).
28. Boboltz, S. Amazing Ways People Are Using 3D Printers For Good, Not Guns. http://www.huffingtonpost.com/2013/11/15/3d-printer-inventions_n_4262091.html, (2013) (Date of access: 28/08/2014).
29. Kitson, P. J., Rosnes, M. H., Sans, V., Dragone, V. & Cronin, L. Configurable 3D-Printed millifluidic and microfluidic 'lab on a chip' reactionware devices. *Lab Chip* **12**, 3267–3271 (2012).
30. Tong, J., Zhou, J., Liu, L., Pan, Z. & Yan, H. Scanning 3d full human bodies using kinects. *IEEE T. Vis. Comput. Gr.* **18**, 643–650 (2012).
31. Aziz, T., Waters, M. & Jagger, R. Analysis of the properties of silicone rubber maxillofacial prosthetic materials, *J. Dent.* **31**, 67–74 (2003).

Author contribution

Y.H. proposed the SPPC method, wrote the main manuscript text and G.X. performed experiments, prepared figures 1–5, 9–10. J.F. planned the research, prepared figures 6–8, and edited the paper.

Additional information

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