Development of a Desktop Food Printer for Dough Extrusion

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***Abstract*—Food printing is increasingly being explored for mass customization of food. This study reports the development of a desktop 3D printer for printing cookie dough. Specifically, the effect of different extruder profiles on the properties of the extruded dough, are experimentally evaluated to obtain an optimal design which consists of a screw, connection profile between the cartridge and the syringe, and nozzles. Three different nozzle designs, namely, conic, fat, and skinny nozzle profiles are tested. The conic nozzle design gives a good balance between the speed of extrusion and extrusion consistency, compared with the other designs. It is further modified to add a straight tube-like section to improve the extrusion consistency. This study demonstrates the importance of dough extruder design in food printing.**

***Index Terms*—food printer design, food printing, dough printing**

I. Introduction

Digitalizing food printing has a great potential of producing customized food with complex geometries, tailored texture, and nutritional content. As the population gets older, an estimated 15 - 25% of this population experiences swallowing difficulty [1] and they obtain nutrition from pureed food, most of which is unappealing and unappetizing. This may result in further deterioration of health. Food printing is a conceivable way of providing soft, nutritious and innovative textured food for the elderly. This enables the mass customization of food to meet individual customer needs and shortens the supply chain from producers to end consumers, ensuring freshness.

A range of 3D printing methods has been utilized for food printing, such as selective laser sintering/hot air sintering, hot-melt extrusion/room temperature extrusion, binder jetting, and inkjet printing [2]. Among them, the extrusion-based 3D food printing is the most widely adopted method. The ideal target of the extrusion-based 3D food printing is to achieve the output of the conventional food extrusion processing physically with a digitalized design and a personalized nutrition control.

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The extrusion process in food printing is a digitally-controlled, robotic construction process which can build up complex 3D food products layer by layer [3]. It starts with the loading of material, pushing the material out of the nozzle in a controlled manner, moving the material stream according to a predefined path, and eventually bonding the deposited layer to form a coherent solid structure.

Researchers have studied rheological properties of extruded food materials and explore their influences on flow conditions, viscosity, and self-supporting structures. Liu *et al*. [4] examined the rheological properties of a mixture of mashed potatoes and potato starch to evaluate its characteristics during printing. Wang *et al*. [5] revealed that the rheological behavior of fish surimi gel with sodium chloride (NaCl) in food printing. The relationship between extrusion process parameters and extruded food pieces has also been discussed. For example, the layer thickness is determined by the stage speed, extrusion rate and diameter of the nozzle. However, the relationship between the extruder design and extrusion process has not been discussed much.

In this study, a desktop Food Printer is designed to print cookie dough, since cookies are regarded as the most available snack for everyone. The printer aims to smoothly extrude natively printable materials like dough, cheese, frosting, creamy peanut butter, jelly, and Nutella at room temperature, and fabricate complex confections with high repeatability, which are difficult to make by hand.

The extruder design is discussed which consists of a cartridge, screw, nozzle, and the connection profile between syringe and cartridge, with the target to optimize food printing process.

II. Extrusion Based Food Printer

A. Introduction to Extrusion-Based Food Printing

The current extrusion-based food printing starts with designing a virtual 3D model. Slicing software translates this model into individual layer patterns and finally generates machine codes for printing. After uploading the codes to a printer and choosing a preferred food recipe, the food printing starts. According to the layer patterns

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generated from the 3D model, the extruded material is dispensed either by moving the nozzle above a motorized stage or by moving the stage underneath the nozzle to form a layer. Each layer welds to the previous layer on the stage and forms a layer based 3D structure. The printed foods may go through a post-deposition cooking process after printing.

B. Desktop Food Printer Design

The extrusion-based food printer consists of a multi-axis stage and one or more extrusion units as shown in Fig. 1. The desktop food printer developed in Fig. 1(a) is based on delta configuration. Compared with the Cartesian configuration, the Delta configuration printers are cheaper and faster and can fabricate larger volume food piece in a shorter time period. This configuration is not so precise in position control but is sufficient for digitalized food fabrication, which is not so demanding on precision. However, when the printhead loaded with liquid material (such as melted chocolate) is moving at faster speed, the rapid acceleration/deceleration may cause liquid vibration in the printing process. Thus, the extrusion process may become unstable. A modified Delta configuration is suggested. Instead of moving the dough extruder, this design moves the printing area and keeps the extruder stationary mounted on the top platform of the food printer.

This printer design has a compact size and low maintenance cost but long fabrication time [6]. With the aid of computer control, such printers can manipulate food fabrication in real time.

The screw-based extrusion is applied in this printer design as Fig. 1(b). In general, the inner wall should use a non-sticking material with a smooth finish to minimize the energy consumption during the food extrusion process and to allow easy sterilization after extrusion. A streamlined connection between syringes/food cartridges and nozzles is expected to mediate the extrusion force. For the purpose of environmental friendliness, a refillable food cartridge design is applied.

To print foods that are both edible and safe, food-safe materials are used including the syringe that stores the material to be printed, the printing stage where the printed food piece stands, screw and certain machine parts.

As shown in Fig. 1 (b), food materials are fed into the cartridge and transported to the nozzle by a screw for continuous printing. In this screw-based extrusion, the food cartridge is designed to have a wide opening on top for material loading, followed by the narrower tube structure (syringe) and the extrusion nozzle. During the printing process, the screw driven by the motor continuously brings the materials downwards and passes through the extrusion nozzle with a minimum disturbance from air bubbles.

This printer is controlled by an Arduino Mega using a modified firmware from RepRap (www.reprap.org). The Arduino controls both three step motors to position the printing area and a step motor NEMA 17 for dough extrusion. The extruder is mounted on top of the printing stage so that it is easy to install the extruder and refill the cartridge.

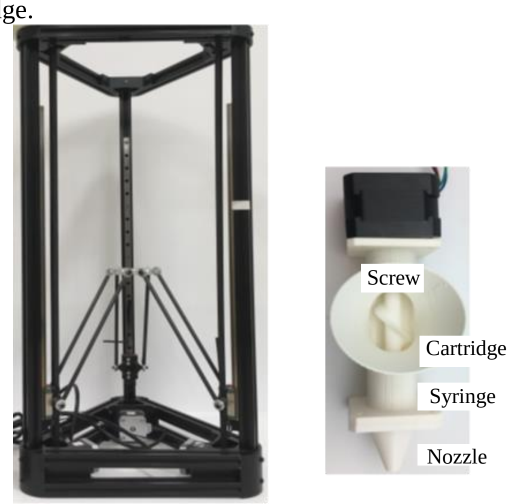

Figure 1. (a) Dough extruder platform, (b) Extrusion unit.

C. Dough Ingredients

Basic cookie dough employs 4 main ingredients: oil (fats), sugar, flour, and water [7]. Oil is added to lubricate the flour and prevent long protein chains. Flour can react with water to form gluten, a protein that gives cookie products the strength, elasticity and crispy texture. The printing dough recipe used in this project is modified from the standard recipe used by Zoulikha *et al.* [7] consisting of 55g flour, 16.5g sugar, 27g oil, and 13g of water.

III. EXTRUDER DESIGN FOR DOUGH PRINTING

A. Screw Design

The screw is used in the food printer to compress the dough out of the extruder. Higher pressure may squeeze out the oil from the dough, thus affecting the composition of the dough. In order to achieve a balance, a screw is designed as shown in Fig. 2.

The larger pitch on the right side helps to collect as much dough as possible from the cartridge before pushing it downstream. The screw has a decreasing pitch from the right to the left so as to raise the pressure by compacting the amount of dough from the syringe to the nozzle. This screw is attached to the shaft of the extrusion motor NEMA 17, hence the screw dimension should match the dimensions of the motor shaft.

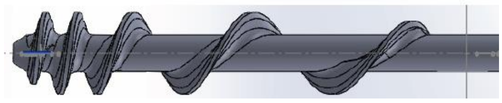

Figure 2. Screw design.

B. Connection Profile

To connect the cartridge and syringe, the two connection profiles are suggested: the smooth bore and the grooved bore (Fig. 3).

The grooved bore design can be modeled as triangle shape which results in 1mm radius deduction on the syringe capacity. In order to ensure that the syringe can hold the same volume of dough, the smooth bore syringe is 1mm smaller than the grooved bore. This ensures that the two syringes can hold and transport the same amount of dough per unit length for further testing and comparison.

The syringe with grooved bore generally performs better than that of the smooth syringe for the same nozzle profile in terms of the extruded dough. Thus, using the grooved bore to connect the cartridge and syringe generally help the extrusion process.

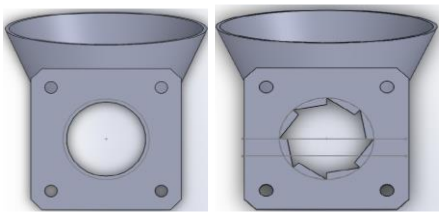

Figure 3. Smooth bore and grooved bore

C. *Inlet of the Extruder Nozzle*

Two types of inlet with/without support to the rotating screw are designed as Fig. 4. The nozzle, which is connected to the end of the syringe can be used to further stabilize the screw during the extrusion by supporting as Fig. 4(b). In other words, the screw is supported at both ends: one at the motor side and one at the inlet of the nozzle. This may prevent the vigorous movement of the screw. Even though a more stable extrusion is achieved, this support design hinders the flow of the dough. Hence, the mass extruded for the grooved bore without support is higher than that of the grooved bore with support.

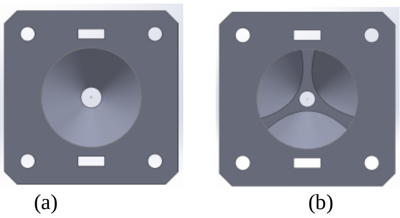

Figure 4. Inlets to the extruder nozzle, (a) without support, (b)with support to the rotating screw

D. *Extruder Nozzle Design for Dough Printing*

Our target is to print a market cookie in 1 minute with an average weight of 12g per cookie [8]. According to Campbell and Spalding [9], two main factors contribute to the material flow rate out of the extruder, namely the rotational motion of the screw, and the back pressure as equation (1).

$$Q_{out} = Q_{rot} - Q_{back} \quad (1)$$

Q_{out} is the total flow rate of the dough out of the extruder;

Q_{rot} is the flow based on the rotational motion of the screw;

Q_{back} is the backflow due to the back pressure.

The back pressure Q_{back} is generated against the screw rotating direction when trying to push the material forward, and this pressure is higher at the outlet of the extruder nozzle due to the compression of the nozzles.

The extrusion nozzle design includes nozzle diameter and profile. Smaller nozzles may lead to the thinner layer thickness, better food surface. Due to the reduction in diameter from the inlet to the outlet of the nozzle, the same amount of material will try to fit into a smaller space thereby compacting and compressing the dough to a higher pressure. Thus, the profile of the nozzle will certainly affect the flow rate of the dough. In this study, the outlet diameter of the nozzle is 5mm, the nozzle length is 30mm, and the screw rotates at 1200mm/min. Three nozzle profiles are designed as shown in Fig. 5 (a-c).

A detailed study of the extruder nozzle design in terms of extrusion speed, consistency, and precision is very necessary. The extrusion speed is measured by the mass of the dough extruded per unit time. Consistency means that the extruded dough stream is smooth and continuous. Precision is usually dictated by the nozzle's outlet diameter.

From Fig. 5(a), it is clear that the conic nozzle has a constant pressure gradient from the inlet of the nozzle to the outlet. While the fat nozzle in Fig. 5(c) has a lower pressure gradient, and the skinny nozzle in Fig. 5(b) has a higher pressure gradient. The pressure gradient affects the extrusion speed and the consistency.

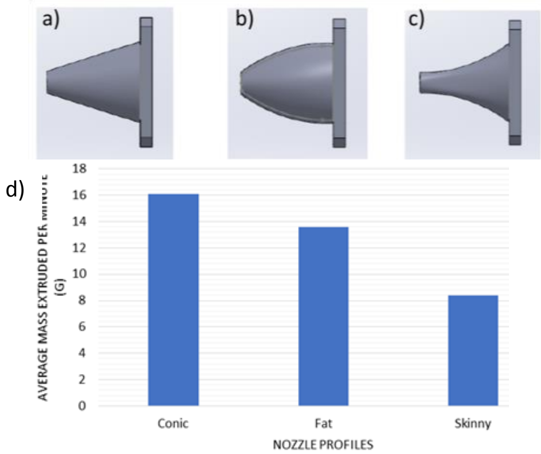

Figure 5. Three nozzle profiles. (a) Conic, (b) Fat, (c) Skinny, and d) Average mass extruded per minute.

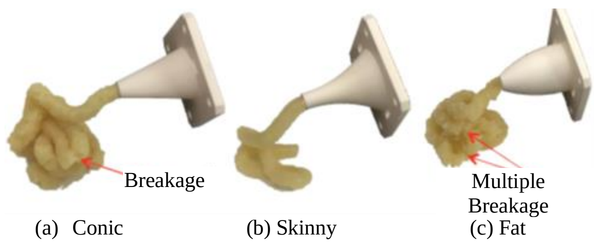

Figure 6. Extrusion consistency for nozzles

A dough mixture (55g flour, 16.5g sugar, 13g water, 27g oil) is extruded through the three nozzle types for one minute as shown in Fig. 5 (d). The dough fed to the cartridge is 24g and the average mass extruded per minute is recorded. It is 16.1g, 13.6g, and 8.4g for the conic, fat, and skinny nozzle respectively. It is obvious that the conic one provides the highest speed of extrusion compared to the fat and skinny nozzles. The fat nozzle's extrusion speed is about 84% of the conic while the skinny is about 52% of the conic.

Fig. 6 shows the consistency of the extruded stream from the three nozzles. Despite the slow extrusion speed, the extruded dough stream from the skinny nozzle provides very smooth extrusion, and almost no breakage, followed by the conic nozzle with some breakages and quite a rough surface. Lastly, the extruded dough stream from the fat nozzle shows a very rough surface with multiple breakages, which is difficult to be used for food printing purpose. Both extrusion speed and extrusion consistency are critical in food printing. To balance them, the next step is to improve the conic nozzle for a better extrusion consistency.

In Fig. 5(c) at the end of the extruder nozzle, the skinny nozzle presents a straight tube-like part. This may give additional compression to the dough, reduce the chance of breakages and push it in a straight manner. As such, a straight tube is proposed and added to the original conic extruder design to improve consistency, but decrease the extrusion speed. Three different straight lengths at 5mm, 10mm, and 15mm are explored while the dimension of the conic part remains unchanged, as shown in Fig. 7 (a)-(c). The average mass extruded per minute and the extrusion consistency for each design is shown in Fig. 7(d) and Fig. 7 respectively.

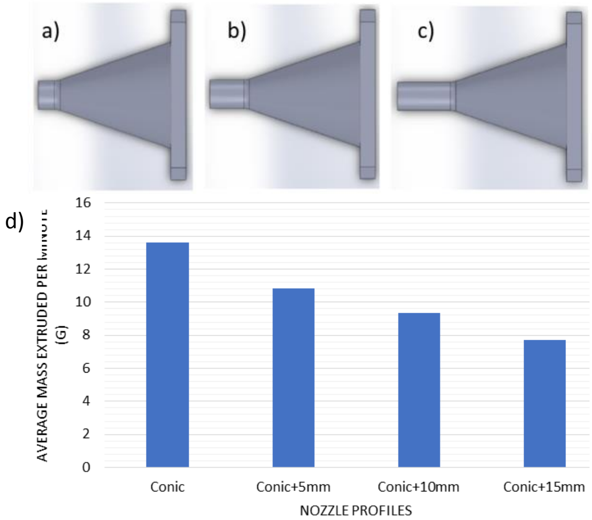

Figure 7. (a-c) Conic nozzle with straight tube at (a) 5mm, (b) 10mm, and (c) 15mm, and d) Average mass extruded per minute

From Fig. 8, it is evident that adding the straight tube on the conic nozzle increases the consistency of the extrusion but decreases the speed of the extrusion. The speed of extrusion drops to about 81%, 70%, and 58% (10.82g, 9.36g, and 7.72g) of the original conic nozzle design for 5, 10, and 15mm of straight tube respectively.

For the 5mm straight tube, the surface is still rough with some breakages. For 10 and 15mm, the consistency is much smoother and similar to the consistency of the skinny nozzle. In general, the longer the dough stays in the extruder, it has more time to compress the dough and hence improving the consistency. While the shift from 10 to 15 mm does not show much improvement in terms of consistency but significant drop in the extrusion speed. Hence, the 10 mm straight tube is the optimal length of the conic nozzle.

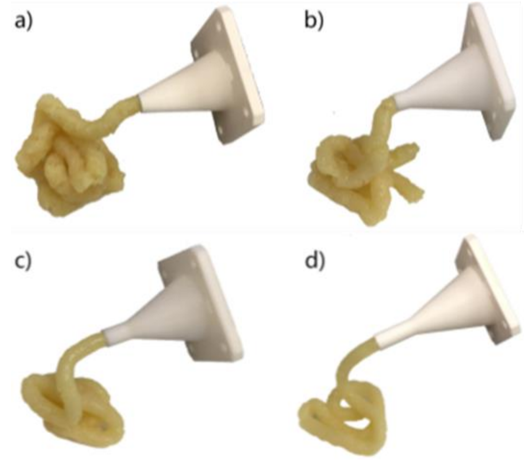

Figure 8. Consistency of conic nozzles a) normal conic nozzle, and conic nozzle with straight tube at b) 5mm, c) 10mm, and d) 15mm

IV. Discussion

In the below sections, the extrusion speed of dough with various nozzle profiles, their consistency, and design improvement are discussed.

A. *Extrusion Speed of Dough with Various Nozzle Profiles*

From the experimental results in Fig. 4, the extrusion speed of the different nozzles can be ranked as conic > fat >skinny, whereas in terms of consistency, it is skinny > conic > fat. To better illustrate this, the three nozzle profiles are analyzed, where the distance between the inlet and the outlet of the nozzle is 30mm, the outlet and inlet radius is 2.5mm and 12mm respectively.

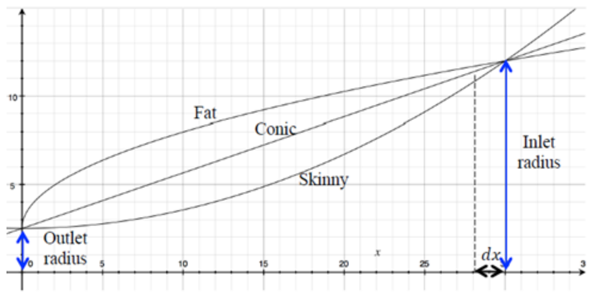

Figure 9. Models of the three nozzle profiles

As seen from Fig. 9, with the same dx from the inlet, the pressure difference will be greater for the skinny nozzle. This is because the cross-sectional area of the nozzle decreases significantly after the inlet. The smaller the cross-sectional area can produce the greater back-pressure. This effect adds up over the entire distance between the inlet and outlet and makes the dough extrusion process slower for the same distance between the inlet and the outlet.

The pressure of the fat nozzle should be less than the conic nozzle, hence leading a higher extrusion speed. While the experimental data suggests that the fat nozzle only performs at 84% of the conic nozzle's extrusion speed. Clearly, another factor is at work as well. The nozzles' extrusion speed is under the mutual influence of the back pressure and the vertical component of pushing force as discussed below.

B. Consistency of Dough Extrusion with Various Nozzle Profiles

The dough is generally compressible [10]. Longer extrusion time may lead to more homogenous structure and composition, and fewer air bubbles, hence better extrusion consistency.

This explains that the skinny nozzle is superior in terms of the extrusion consistency under the force generated from the rotating screw. For the fat nozzle under the same extrusion speed, it will produce a lower mass with breakage.

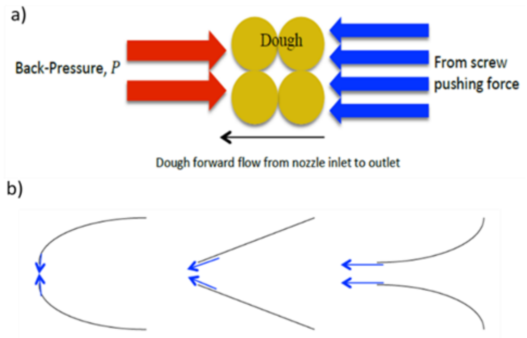

Figure 10. (a) Dough compression under the back-pressure and rotational force from the screw, and (b) Extrusion force under the three nozzle profiles

Fig. 10 (a) shows the dough forward flow from the nozzle inlet to outlet under the back pressure and the screw rotating force. Fig. 10 (b) shows the directions of the pushing force at the outlet of the three nozzles. The skinny nozzle has an almost horizontal force leading to a smooth extrusion. In both the conic and the fat nozzle, the force has both horizontal and vertical components when pushing the dough out of the outlet. This vertical component may change the direction of extrusion, and the fat nozzle with the highest vertical component leads to the lower extrusion speed, more breakage, and poor consistency.

C. Improvement of the Cartridge Design

In the current cartridge design, the dough is pushed both outwards and upwards. Due to the rotating motion of the screw, some portion of the cookie dough is pushed out of the cartridge especially between the open to the syringe. In order to tackle this issue, the cartridge needs to be modified. For example, using vertical wall design instead of slanted.

To reduce the friction between the wall and the dough, the better surface coating on the inner wall with food grade material is suggested.

V. Conclusion and Future Work

A desktop 3D food printer is designed and tested in this study. The speed of extrusion and extrusion consistency are the two important evaluation criteria. Three different nozzle profiles are designed (conic, fat, and skinny) and their characteristics under extrusion are evaluated. The experimental results prove that conic nozzle profile with a 10mm straight tube at the outlet achieves a good extrusion speed and consistency. With this design, the average mass extruded per minute with good extrusion consistency achieved is 13.3g/min, which is higher than the current market standard. In the future, a multiple nozzle system will be designed to print other auxiliary ingredients.

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