Transformative Appetite: Shape-Changing Food Transforms from 2D to 3D by Water Interaction through Cooking

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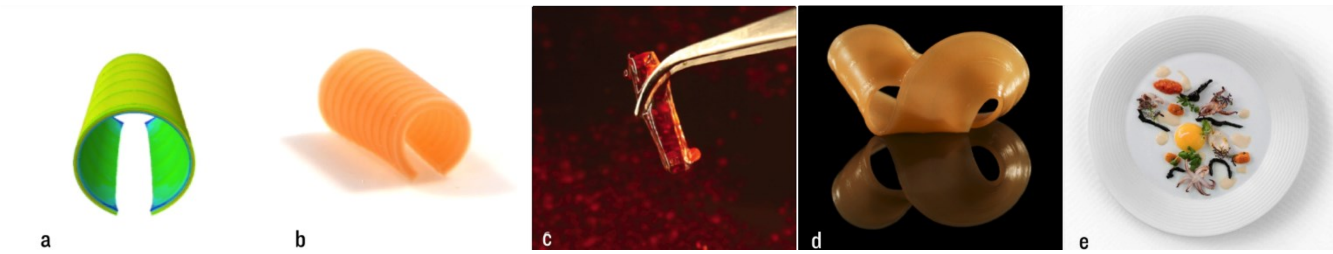

Figure 1. (a-b) Bending simulation of edible film and its corresponding actual sample; (c) self-wrapping water sushi; (d) 3D food from flat 2D film; (e) dish design with squid ink flavored twisting noodle.

ABSTRACT
We developed a concept of transformative appetite, where edible 2D films made of common food materials (protein, cellulose or starch) can transform into 3D food during cooking. This transformation process is triggered by water adsorption, and it is strongly compatible with the 'flat packaging' concept for substantially reducing shipping costs and storage space. To develop these transformable foods, we performed material-based design, established a hybrid fabrication strategy, and conducted performance simulation. Users can customize food shape transformations through a pre-defined simulation platform, and then fabricate these designed patterns using additive manufacturing. Three application techniques are provided - 2D-to-3D folding, hydration-induced wrapping, and temperature-induced self-fragmentation, to present the shape, texture, and interaction with food materials. Based on this concept, several dishes were created in the kitchen, to demonstrate the futuristic dining experience through materials-based interaction design.

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Design

INTRODUCTION
The concept of 'flat packaging' was coined by IKEA, a Swedish furniture company, which manufactures 2D furniture segments for assembly into 3D furniture by people in their own homes. This concept enables the company to benefit from low shipping costs due to compactness of the 2D segments while maintaining the desired function and appearance of the 3D end products.

Here we propose a similar concept for the food industry, where edible materials are manufactured into highly compact 2D segments and transformed in the kitchen or on the dining table into 3D structures, which bring different textures and eating experiences to diners. We combine material science, computer-aided design and additive manufacturing to enable autonomous transformations in pre-defined ways, which liberates users from tedious cooking tasks. Specifically, through three techniques and dish examples, we aim to demonstrate that the 2D-to-3D transformation via hydration process is good for 1) creating unique mouth feel textures and shapes to enrich the eating experiences; 2) achieving programmable food transformations; and 3) save space during shipping and storage.

We believe that this concept and the technologies we developed for enabling food transformation via hydration will contribute to the evolution of more cost-effective food manufacturing and futuristic dining cultures. We feel that their most immediate applications will be found in upgrading quality of compact foods that are widely used in outdoor activities.

CONTRIBUTION

Design through Edible Material Innovation

- Characterized hygromorphic behaviors of three major food materials: gelatin (protein), agar and cellulose (fiber), as well as starch (carbohydrate), for designing bi-layer edible films.
- Explained the bending mechanism and simulated the sequential bending behaviors through finite element analysis.

Fabrication Practice and Computer-Aided Design

- Established a simplified simulation platform that combines material mechanics and geometric design, to enable users to design different shape transformations.
- Proposed a material fabrication strategy to create controllable transformation geometries.

Food Design

- Proposed autonomous shape-changing food that reduces shipping costs, enriches eating experiences, and saves storage space.
- Presented a new way to enhance interactions between diners and food through shape transformations from 2D-to-3D in the kitchen.

RELATED WORK

Material Based Shape-Changing Interfaces

Researchers in HCI have increasingly been working on material aspects of shape-changing interfaces, envisioning the embedded programmability through the design of material composition and structure, or, 'computational' materials with pre-programmed interactivities [1-4]. Rasmussen et al. [5] proposed a set of novel interaction modalities enabled by shape-changing interfaces, including functional aims (dynamic affordances, communication and force feedbacks) as well as hedonic aims (emotional experience and aesthetics). Coelho et al. further pointed out a material-based approach to design shape-changing interfaces [6]. In their paper, they described transformative materials that respond to different stimuli types. Our work contributes to this vision by introducing this approach to the application of food.

Water-Triggered Shape Transformation

Recently, materials that can change shape through interaction with water have been commonly used in many research domains, including drug delivery systems [7], interactive architecture [8, 9], smart household objects [4], motor generators [10] and biomimetic morphologies [11]. These smart materials exhibit different shapes when adsorbing or desorbing water, accompanied by swelling or shrinking with volume or structure change. To achieve high programmability of the final shape, they use either rigid shape constraints (e.g. fibrils or hinges) or uneven stress distribution (e.g. material geometry alignment) [12] through anisotropic swelling. All of these actuation system use synthetic materials as key components, which prevent them from being safe for consumption in the food industry - to our knowledge, we have not found, to date, any system completely made of edible, natural materials.

Shape-Changing Food and Digitally Fabricated Food

Food shape is an important factor for both the cooking and dining experience. Traditionally, shape change in food materials is observed and sometime used as a cooking indicator. For instance, ravioli (an Italian pasta) begins to inflate during boiling (due to starch hydration accompanied by vapor generation inside pasta), and floating signifies the complete boiling of the pasta. Recently, the design of interactive food has become an important research topic [13], and has been demonstrated within the context of HCI, where stimuli such as pH [14], lighting [15], and food cost [16] were used to enhance the interactivity between a diner and food materials. In particular, Kan et al. developed a series of edible organic sensor-actuators that respond to pH and transform in shape, color and odor [14]. Their paper envisions the wide use of such organic materials in material-mediated interaction design including food. It described shape-programmable pasta triggered by pH, and introduced a few use scenarios where shape-transformable pasta can be valuable: flavor and sauce retention, sensory augmentation, and user-based customization. Moreover, digital gastronomy [17] was proposed as a vision of how food can be prepared with property customization via a variety of digital fabrication machines including 3D printers and CNC machines. We are inspired by this domain of research, and propose a deeper investigation into the transformation triggered by hydration processes instead of pH, with hope that more stimuli types can be included to trigger shape -programmable food; in addition, we focus on investigating a practical use scenario - flat packed food - to save shipping and packaging cost.

MATERIALS EXPLORATION

Edible Materials Interact with Water

Cooking processes can be divided into two categories: hydration and dehydration. Each may cause shape transformation. These phenomena have been widely observed in kitchen during cooking. For example, noodles grow thicker as they are boiled or steamed, while potato strips inflate as they are baked or fried. In this paper, we focus on the hydration process and quantify the transformation of food materials during water adsorption.

We found most of the food gels hydrate and change volume when absorbing water through hydrophilic interaction within their molecular or intermolecular structure. One way to quantify a material's ability to hydrate is to use the swelling index (I_s), which is defined in Equation 1, where W_s is the weight of the swollen food material, and W_d is the weight of the dry food material.

$$I_s(\%) = \frac{W_s - W_d}{W_d} \times 100 \qquad \text{(Equation 1)}$$

We measured swelling index of a few major edible components (Figure 2), which showed that protein (gelatin), carbohydrate (starch), and soluble fiber (agar) can all absorb about five times its own weight within ten minutes (in film form), while insoluble fiber (ethyl cellulose film) cannot absorb any water. This finding is the basis of designing shape transformation through volume change by introducing anisotropic swelling behavior within the food's composite structure.

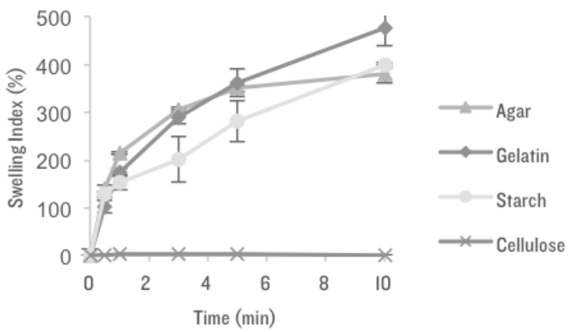

Figure 2. Comparison of swelling index of four different edible materials at 20°C.

Material Selection Rationale

In this paper, we focused on gelatin, and studied the shape-change behavior of gelatin-cellulose composite films during hydration through cooking. Our reasons for focusing on gelatin are multifold. First, gelatin dissolves well in solution before the gelation process, ensuring uniformity of the food gel before drying. Second, gelatin materials at different molecular weights (or Bloom numbers) are commercially available, enabling us to easily and precisely control their chemical and physical properties. Third, there are different sources of gelatin (e.g. from porcine skin, cattle bones), to suit diners' specific needs. Fourth, comparing with other edible materials (such as starch), it is much easier to prepare a flat film, due to the high flatness of the gelatin-air surface and its low attachment to the supporting holder (e.g. petri dish).

To form a composite structure, we choose ethyl cellulose as the water barrier, based on its low water adsorbing capacity and high alcohol solubility. The unique properties of ethyl cellulose compared with other types of cellulose (e.g. methylcellulose) enables high-precision digital printing and large-scale screen printing, by which ethyl cellulose fiber can be easily deposited through solvent evaporation. In literature, tensile stress of cellulose fiber is a well-known parameter and can be used to manipulate shape constraint effect and obtain a well-controlled transformation.

Temperature Dependent Swelling/Melting

While temperature modulation in cooking is commonplace, we have not found previous work using temperature modulation for controlling and manipulating food shape transformation. We aim to use temperature as a parameter to change swelling and melting of edible materials. To achieve this, we first studied the swelling behavior of these edible materials at different temperatures in water. As expected, at high temperature, edible films can absorb water at a faster rate than in cold water (Figure 3). This can be explained by Fick's law (Equation 2), where diffusion flux (J) is dependent on both diffusion coefficient (D) and the concentration at certain location ($\frac{\partial \varphi}{\partial x}$), where the diffusion coefficient (D) is a function of temperature (T) and proportionality constant (D_0) (material specific). E_A and k are constant.

$$J = -D\frac{\partial \varphi}{\partial x} = -(D_0 e^{-E_A/(kT)})\frac{\partial \varphi}{\partial x} \qquad \text{(Equation 2)}$$

Gelatin has a very low melting point, which becomes an important parameter in our design. High molecular weight gelatin begins to melt at ~40°C, and low molecular weight gelatin begins to melt at ~20°C. By adjusting hydration temperature, we can switch physical status of gelatin from a solid state to a liquid state. With these methods, we are able to prepare a composite structure and create temperature-sensitive hinges using low molecular weight gelatin to achieve programmable breakage due to melting.

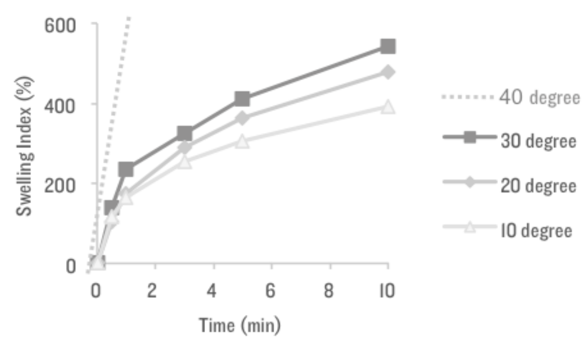

Figure 3. Temperature dependent swelling of gelatin.

COMPOSITE MATERIALS DESIGN

Designing Substrate Film

In order to design different physical transformations, we need to prepare a film with density distribution. We found that when preparing a film in a petri dish and evaporating water only from the top of that film, the desired density heterogeneity could be achieved (Figure 4).

The solid-air boundary contains a higher concentration of gelatin, due to surface aggregation of the solids towards the interface. After forming a dried top layer, water evaporation in lower portion of the film becomes restricted. This results in the formation of gelatin film with a dense top layer and a loose, porous bottom layer. We validated this hypothesis by scanning electron microscope (SEM) characterization (Figure 4), where the top layer of the film is much denser than the bottom layer.

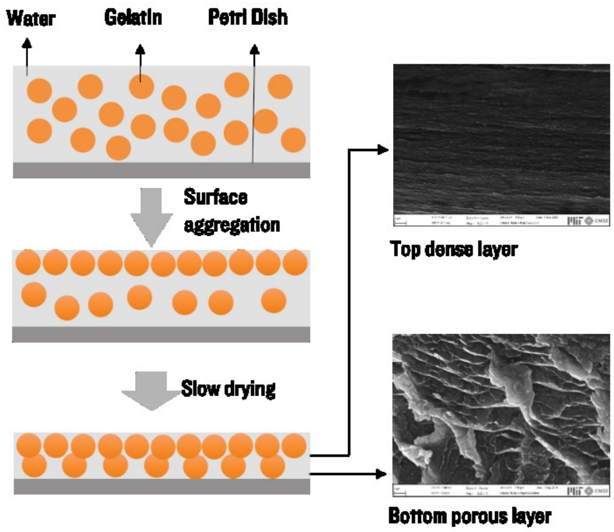

Figure 4. Formation of heterogeneous gelatin film.

Adding Shape Constraints/Water Barriers

In order to achieve a controllable bending behavior, we introduce ethyl cellulose strips as both shape constraints and water barriers on top of the gelatin film. This semi-rigid strip structure helps regulate the binding direction and create dynamic shape changes by modulating the top surface's water adsorption rate (mostly due to decreased water adsorption area).

MECHANISMS OF SHAPE TRANSFORMATION

Bending Analysis

When immerging the gelatin film with cellulose strips into water, the bottom layer exhibits a higher water adsorption rate than the top gelatin layer initially, due to a relatively larger water contact area. This initial upward bending direction is always along the longitude direction of the cellulose strip, because it is hard to compress a synergistic swollen top gelatin layer in the direction perpendicular to the cellulose strip (high expansion freedom).

Gelatin film is composed of a top layer (dense structure) and a bottom layer (porous structure) with a thickness ratio about 1:1 (based on SEM images). Thus, the overall water adsorption capacity of the top layer is higher than the bottom layer. After a specified duration, the folding direction reverses and the whole film bends downwards; the top layer has a greater capacity to absorb water (and swell) albeit at a slower rate than the bottom layer. The specific duration depends on the water adsorption rate, which can be controlled by designing the coverage of the cellulose on the gelatin surface, as well as the density of the cellulose strips (Figure 5).

During the hydration process, the gelatin film changes from glassy to a rubber-like state synchronized with water adsorption. The direction of bending depends on the stiffness of the cellulose strips at that time point. When cellulose is thick and stiff (shape constraint dominant), the film will bend towards the direction perpendicular to the cellulose strip. Otherwise, the film will prefer to bend along the direction of cellulose (flexible skeleton).

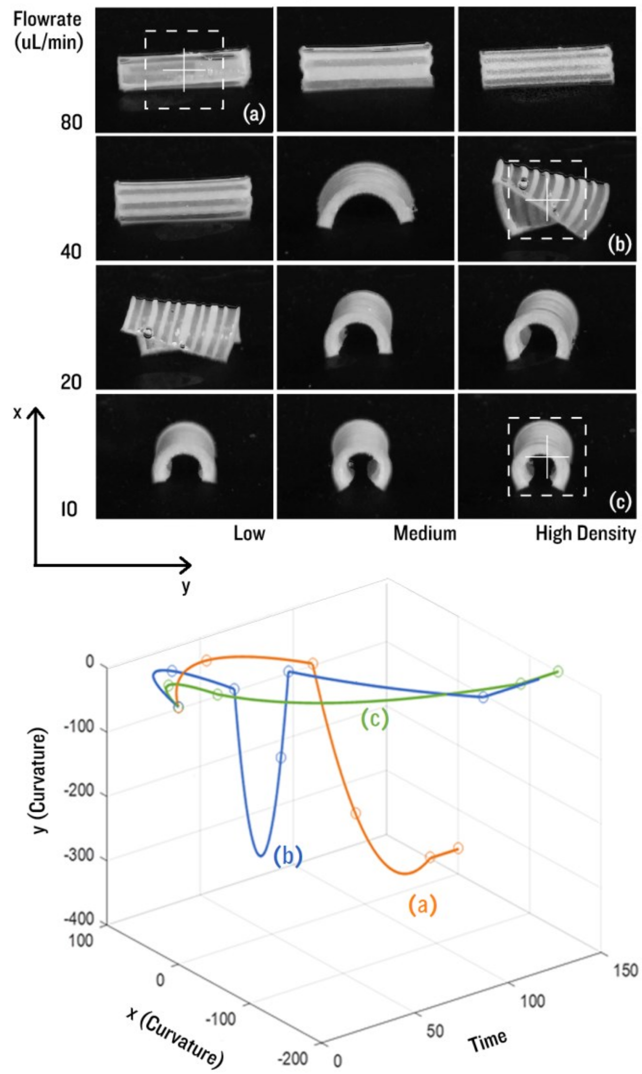

Figure 5. Bending curvature design by cellulose thickness and surface coverage density.

Mechanics Analysis

In short, we hypothesize that the cellulose strip has a dual role in controlling shape change of the whole structure. First, cellulose layer can be seen as a barrier for water diffusion, which modifies swelling behavior of the gelation film beneath of it. Second, the cellulose layer is also a mechanical constraint and can be used to tune the bending deformation of the structure. To verify this, we performed finite element (FE) simulations with software ABAQUS. Gelation and cellulose are each modeled as Neo-Hookean material in Equation 3, where μ is the shear modulus, $\lambda_i, i = 1,2,3$ the principle stretch ratio. The shear modulus of the bottom gelation layer is taken as the unit value ($\mu_1 = 1$) and the modulus of the top gelation layer is set to be $\mu_2 = 5$, as the density of the top film is higher than the bottom layer (SEM in Figure 4).

$$U = \frac{1}{2}\mu(\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3) \qquad \text{(Equation 3)}$$

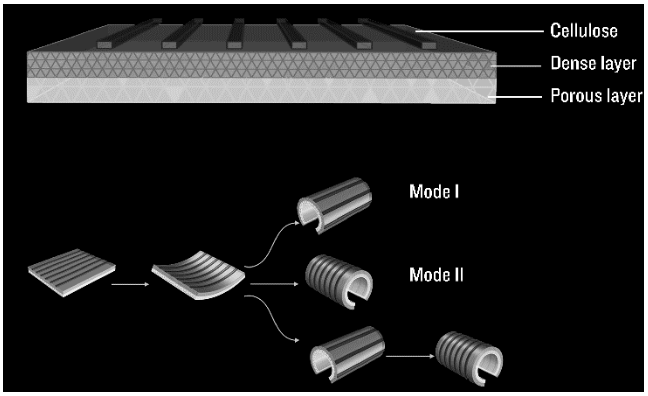

Figure 6. Diagram of three layer film and its sequential bending behavior.

To test the mechanical constraint effect of the cellulose, two set of simulations are carried out with a shear modulus of cellulose as $\mu_2 = 10$ and 25, respectively. The geometry of the structure is: thickness of bottom gelation film $h_1 = 35\ \mu m$; thickness of top gelation film $h_2 = 35\ \mu m$; thickness of cellulose layer $h_3 = 10\ \mu m$; the width of the structure is 15 mm and the height of the structure is 13.8 mm; the cellulose lines are shown in Figure 6. Our FE simulations clearly show that the structure with soft cellulose will choose bending mode I, while the structure with stiff cellulose will choose bending mode II (Figure 7).

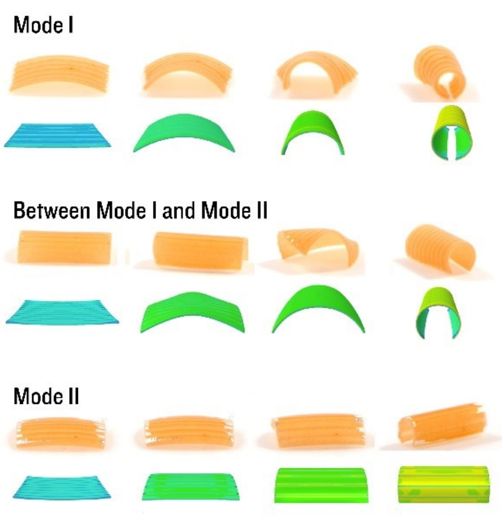

Figure 7. Comparison between actual transformation and simulation using finite element in ABAQUS.

FOLDING DESIGN

Beyond using straight lines as shape constraints to achieve one-dimensional folding, we have also developed two-dimensional folding by using either 2D constraints or distributing 1D constraints within 2D surface (Figure 8). By using curved lines or surface constraints, complex structures such as the flower shape, saddle shape, and cone shape were obtained. This folding principle provides us a basic grammar to design more complex shape transformations by simply manipulating geometry and constraints.

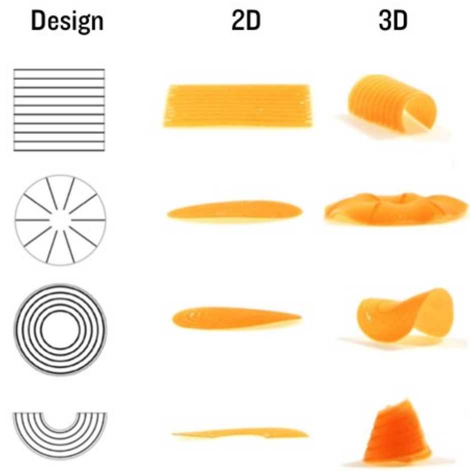

Figure 8. Design primitives (black lines indicate fiber location).

SIMULATION INTERFACE

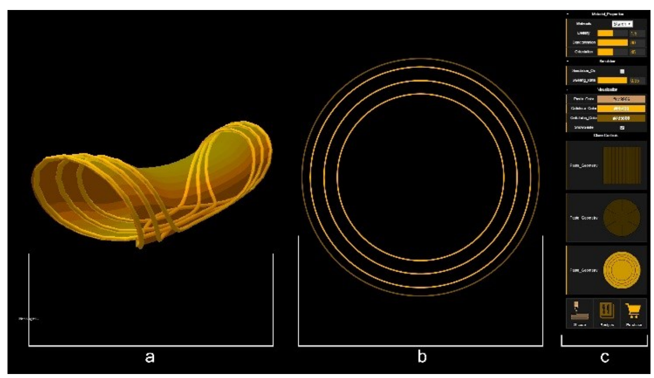

Figure 9. Illustration of user interface: a) transformation preview; b) cellulose constraints preview; c) variable sliders and options.

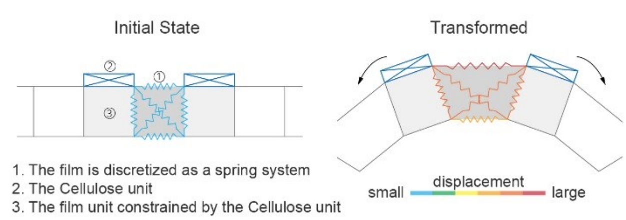

Figure 10. Simulation model units.

To facilitate design and predict the shape transformation of these edible films, we built a digital material design and simulation interface (Figure 9) with JavaScript, Rhinoceros, and Grasshopper. The platform can aid in the design process and interact with the user through the following steps. First, the user can select a variety of shapes for the substrate film. Second, our platform will automatically create the cellulose constraints based on the assigned shape. The user can tune the density, orientation, and thickness of the constraints by dragging sliders. After the constraints are defined, the user can preview the transformation immediately. When the users are satisfied with their design results, they can export support structure to G-code for printing.

To create a real-time preview, we pre-calculated a shape dataset in Rhino and Grasshopper, using a relatively simplified model (Figure 10) compared to our mechanics analysis. By interpolating the pre-calculated shapes in the database, the interface can visualize the result with virtually no computation costs. However, the capability of the design interface is limited by the dataset because the user cannot design shapes which we have not pre-calculated. For the current version, we only have the rectangle, saddle and flower shapes in our dataset.

FABRICATION STRATERGY

We combined wet lab material preparation with digital fabrication to achieve controllable food shape transformations. In doing so, we leverage the advantages of both methods to obtain a scalable and flexible fabrication strategy.

Materials

We procured PerfectaGel Gold gelatin sheets (200g Bloom) from Amazon.com. Low molecular weight gelatin (50-80 g Bloom, from porcine skin, Cat# 48720), ethyl cellulose (48.0-49.5% w/w ethoxyl basis, Cat# 46070) were purchased from Sigma-Aldrich. Food grade ethanol (95% w/v) was purchased from a local liquor store. Screen printing tools were purchased from Blink Art Supply. All other material science equipment was purchased from VWR and all other mechanical tooling was purchased from McMaster Carr. Traditional food materials were purchased from local supermarket.

Preparing Films

Edible films with heterogeneous density distribution were prepared by using plastic large petri dishes (diameter 15 cm) as containers in a wet lab. This method ensures one-directional water evaporation and a controllable density distribution. First, the solid edible materials (either gelatin or starch) were dissolved at a certain concentration (3-12% w/v) at room temperature for complete hydration (about 15 min). The solution was further transferred to a hotplate at ~60°C to ensure total melting of the solids in aqueous solution. We found this procedure could also be performed in a microwave (high heat for 1-2 min, avoid overheating). Conventionally, we use water to prepare a transparent and flavorless film. For adding flavors to the film, we found fruit punch, vegetable juice, and seafood extract can also be added into the mixture or as substitutes for water. Afterwards, varying amounts (12-60 mL) of solution were transferred into petri dish by pipet, to form different thicknesses of gel. The gel was cured at room temperature for about 5 min, and transferred to a windy area with fans to allow one-directional water evaporation (12-18 hours).

Preparing Cellulose Solution

Ethyl cellulose solution was used to create shape constraints on top of dried gelatin films, which control the bending direction during the hydration process due to the rigidity of the printed cellulose fiber. As ethyl cellulose does not absorb water, it can be used as a water barrier to decrease the top surface water adsorption rate. This will also create sequential shape transformations, where bending is firstly upwards (higher surface exposure in the bottom layer), and then downwards (higher overall expansion capacity). The printing solutions were prepared by dissolving ethyl cellulose solid materials in 95% food-grade ethanol (5-30% w/v), in a slightly heated water bath (~50°C).

Digital Printing through xPrint

With the purpose of increasing fabrication precision and customizability, we adapted a the digital printing platform xPrint [18] to deposit the cellulose on top of the gelatin films by an adjustable dispenser mounted on a CNC platform (Figure 11). Several parameters were tuned during printing, including cellulose concentration (5-30% w/v), line gap (1-5 mm), solution deposition speed (5-300 μL/min), gap between dispensing tip and gelatin film (0.1-0.5 mm), and tip diameter (0.008" to 0.024"), to achieve desired cellulose line thickness, height, and area coverage. Compared to previous materials used in xPrint, cellulose prepared in ethanol can easily solidify, potentially clogging the dispenser system.

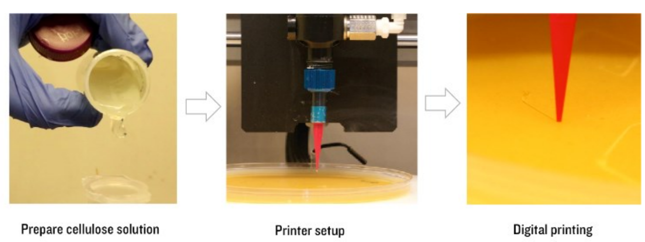

Figure 11. Digital printing process.

We found this was due to the evaporation of the ethanol in the windy fume hood. To reduce clogging, a seal cap with a long tubing outlet was attached on top of the solution reservoir connected with the dispenser. Before each printing, pre-extrusion at high flow rate (50 μL/min) was performed to ensure printing efficacy. Regular cleaning using 95% w/v ethanol was also used to clean the system between runs on different days.

Screen Printing

Beyond digital printing, we also applied screen printing to deposit cellulose, in order to demonstrate the scalability of our method (Figure 12). Similar to traditional screen printing, we substituted the base material with a flat gelatin film, and placed the mask on top of the screen mesh.

Cellulose concentration (5-30% w/v) was adjusted to achieve a desired viscosity, and a squeegee was used to spread the materials to form a thin layer. The height of cellulose depends on the total distance between top surface of mask and the film. This process can be easily scaled up for high volume manufacturing due to high efficiency. Since the cellulose will solidify on the mesh and it is tedious to clean, we also developed a simplified screen printing method without the mesh. Instead of sticking the cut mask by vinyl cutter on the mesh, the mask was directly pasted on the gelatin film. A tiny amount of cellulose solution (< 200 µL) was further spread using squeegee. Rapid peeling of the mask before complete solidification of cellulose is crucial to avoid unintentional removal of the cellulose strips.

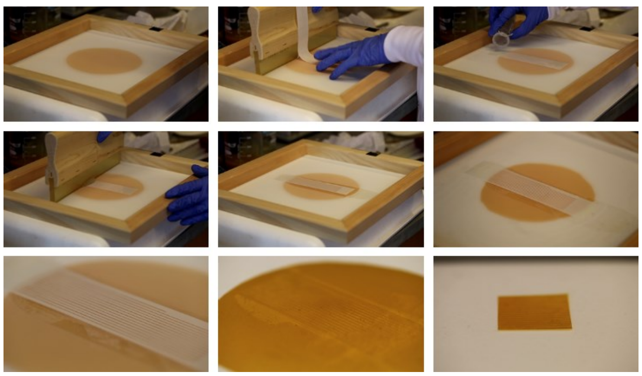

Figure 12. Screen printing process.

FOOD INTERACTION TECHNIQUES

With the above-mentioned fabrication and simulation platform, we developed three techniques to demonstrate the customizability of achieving fragmentation, shape, texture, and interaction of food materials through shape transformation.

2D-to-3D Film

We fabricated different shapes of edible films through modulating both gelatin sheet geometry (e.g. disk, oval shape, S-shape) and shape constraint properties (e.g. cellulose density and thickness, line gap, total coverage). By adjusting these parameters, the rigidity of shape constraints and water diffusion rate can be modulated. We are able to match these fabricated shapes with the traditional molded pasta shapes (Figure 13 a-h), providing an exciting potential solution for making transformable 3D food. In the meantime, we also created new special shapes (Figure 13 i-k) that offer potential for novel dish development.

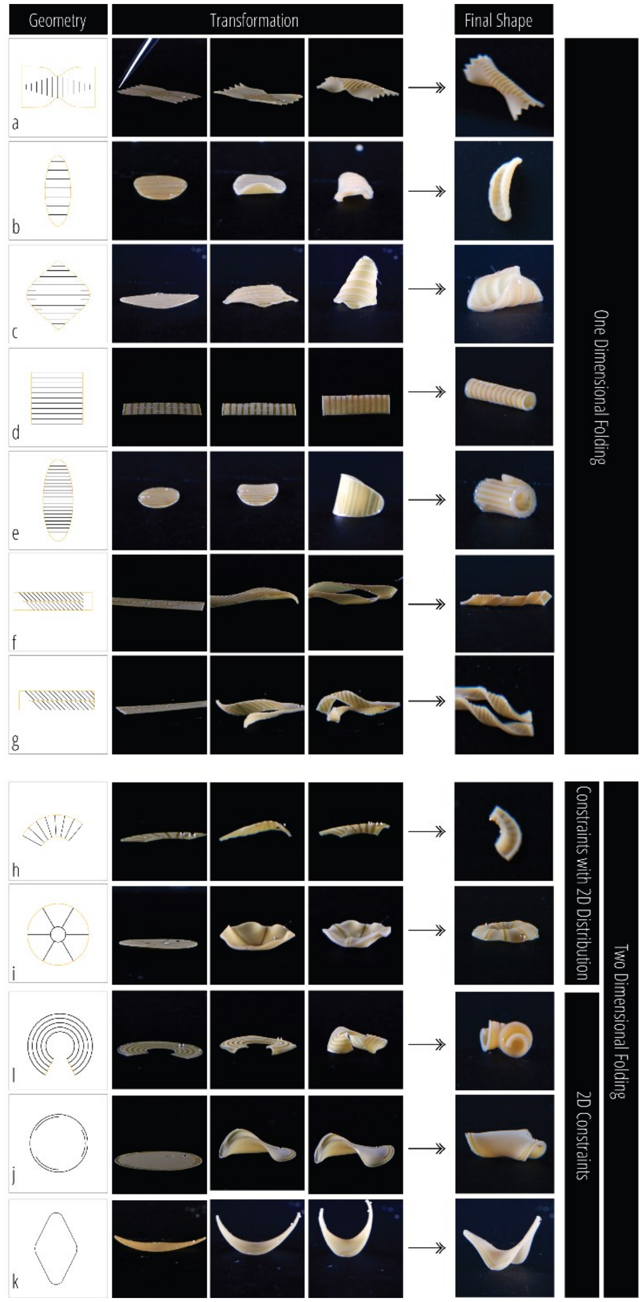

Figure 13. Folding Algorithm.

Self-wrapping Films

Intrigued by interaction between these 2D films and other edible materials, we developed a transparent edible film that wraps fish caviar when immersed in water (Figure 14). We control this transformation by engineering the geometry and thickness of the gelatin film, folding curvature, water temperature (hydration speed), and density of caviar suspended in water.

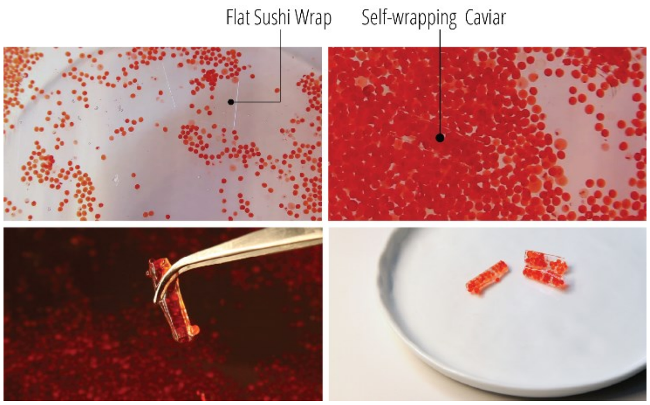

Figure 14. Self-wrapping water sushi.

Temperature Responsive Strips

We made film with two-layer composite structure - the top layer is formed by high Bloom number gelatin, while the bottom layer contains low Bloom number gelatin. When cooking at relative low temperature (~25°C), the linkage formed by high Bloom number gelatin will maintain solid state and hold the long thread shape of the noodle. In contrast, at higher cooking temperature (~40°C), the linkage between segments will be dissolved and noodles will form shortened and twisted segments (Figure 15). In addition, the wrapping direction can be controlled by adding another layer of cellulose on top. We also demonstrated the same idea using starch-gelatin composites.

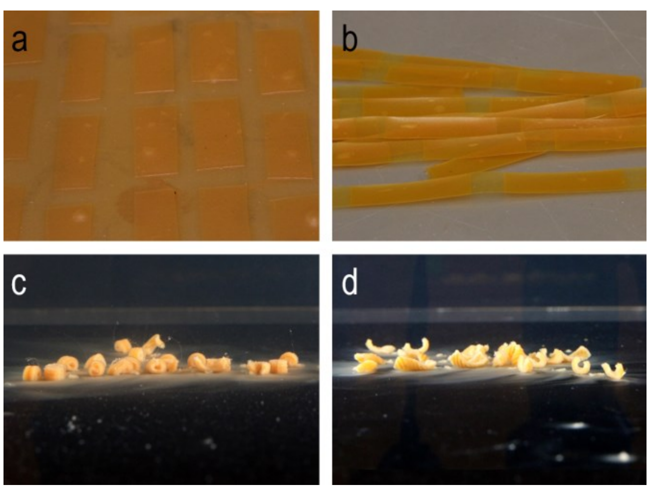

Figure 15. Temperature responsive noodle (a) prepared composite film; (b) strips. Self-chopped pieces in water (c) twisted along edge; or (d) twisted along diagonal.

DISH DESIGN

Co-developed with a chef, we applied the above-mentioned three techniques for designing edible and interactive food that can be served in a restaurant or at home.

Cold Pasta Salad

Considering starch consumption might be regulated for those who suffers from diabetes or obesity, we created transformable fruity pasta out of gelatin and cellulose, which are major components of proteins and fibers, as a heathier food substitute (Figure 16).

Recipe: Prepare edible gelatin gel (6% w/v) with flavored liquid (squid ink, potato extract, or seaweed) in a flat-bottom dish. Dry the film in kitchen with a fan for 12 hours. Digitally print cellulose solution (30% w/v) on gelatin film with the following parameters: line gap (based on geometry), solution deposition speed (20 μL/min), gap between dispensing tip and gelatin film (0.3 mm), and tip diameter (0.010"). Cut the film into different shapes and immerge into water at 30°C. The transformation should occur within 2 minutes.

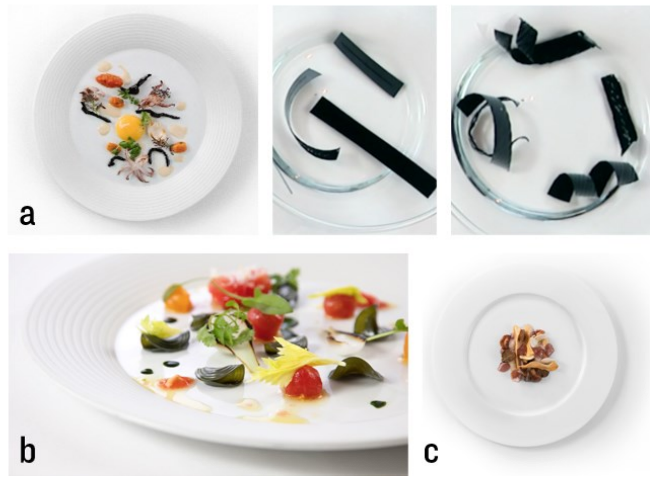

Figure 16. Cold pasta salad design (a) Helix noodle with Point Judith squid, confit egg yolk and white hoisin; (b) Phytoplankton pasta salad with heirloom tomatoes and wild sorrel; (c) Flowering pasta with west coast foraged mushrooms and fermented burgundy truffle.

Cavier Cannoli

Cannoli excellently represents of interactions among multiple edible materials that have distinct flavors, especially in the contexts of taste and flavor. We hope to utilize our current transforming food methods to create a new dish - self-wrapping cavier cannoli, to demonstrate multiple food materials interactivity through designed shape transformation upon hydration. This design also enhances the interactivity between the diner and food itself, and offering new possibilities for the dining environment (Figure 17).

Figure 17. Transparent cavier cannoli with celery and crème fraiche.

Recipe: Prepare edible gelatin gel (6% w/v) in drinkable water in a flat-bottom dish. Screen print cellulose solution (15% w/v) on the gelatin film: line thickness (1 mm), line gap (3 mm). For a comfortable texture in-mouth, prepare a composite film of gelatin-agar without cellulose strips. Cut into square shape (2×2 cm) and emerge it into water with caviar at 35°C. Stir solution to have caviar present on both sides of the film. The transformation should occur within 2 minutes.

Self-chopped Noodle

Noodles have long and thin thread shapes. In a large family, it is often hard to accommodate everyone's requirement when serving noodles as the primary carbohydrate intake. For instance, kids may require soft noodles with shorten lengths for the ease of chewing and digestion, while adults may want longer noodles with chewy textures. So we propose the use of temperature responsive edible materials to meet the different diners' requirements (Figure 18).

Recipe: Prepare a gel with high Bloom gelatin (6% w/v) in seaweed extract. Dry it and cut it into small rectangular shapes (1×2 cm). Afterwards, prepare another gel with low Bloom gelatin (6% w/v) in a seaweed extract as well. Assemble the rectangular high Bloom pieces on the newly prepared wet low Bloom gelatin gel. Dry it for 18 hours. Print cellulose in lines with the following parameters: line thickness (1 mm), line gap (3 mm). Cut into long strips. Prepare a chicken soup at 37.5°C. Dip the strips into the soup and transformation should occur within 5 minutes.

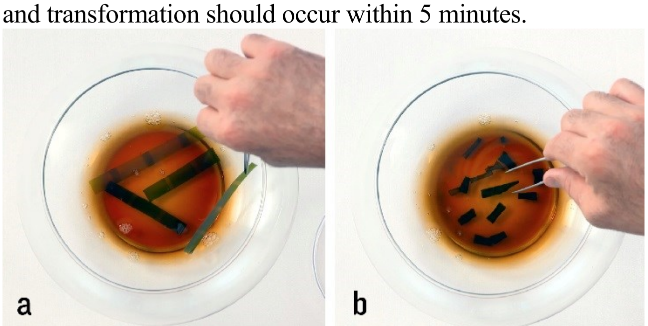

Figure 18. Chicken soup with self-chopped noodle.

DISCUSSION AND FUTURE WORK

Flat-packed Food Challenges and Opportunities

In modern society, food produced locally has become scarce. Much of the food in urban regions is produced remotely and shipped to customer, resulting in pollution to the air due to the emissions of greenhouse gases to the environment [19]. The flat-packed food proposed in this paper, may partially alleviate pollution, by reducing the amount of air shipped during food transport.

Take a package containing short macaroni pasta as an example, the densest packing of tubes (side view of the pasta) in the plane is the hexagonal lattice of the bee's honeycomb (Figure 19) [20]. The packing density (θ) can be calculated in Equation 4. If r = 0.8R, so θ = 67.3%, which means 67.3% of volume in the package is air. If instead we are able to flat-pack pasta, and transform it into 3D shapes during cooking, more than half of the space during shipping and storage will be saved.

$$\theta = \frac{\sqrt{3}R^2 - \frac{1}{2}\pi R^2 + \frac{1}{2}\pi r^2}{\sqrt{3}R^2} \qquad \text{(Equation 4)}$$

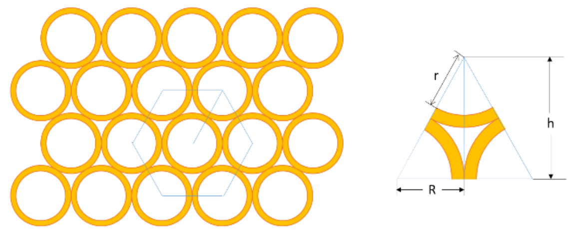

Figure 19. Macaroni pasta by hexagonal packing.

Future Fabrication Techniques

As a further step for our fabrication of shape-changing edible films, we aim to create a platform that will enable individual creation and customization of transforming edible films using off-the-shelf components.

As an example of such, we assembled a twin syringe desktop 3D printer for biological materials using the open source 3Drag printer chassis with Choco syringe extruders from Futura Group Srl. The printer design includes a small refrigeration system to rapidly solidify warmed substrate during printing. Use of the two syringes enables us to print two materials at a time - gelatin and cellulose simultaneously. The temperature control module on the syringe enables maintaining high temperature (50°C) of unprinted gelatin, and it can rapidly cooled down on the cooling panel after printing, to achieve layer by layer printing. The chassis uses a Velleman 8400 control board using Marlin firmware (http://marlinfw.org/). We operate the printer using Repetier-Host client software from Hot-World GmbH & Co with the GCode generator Slic3r from slic3r.org.

To print edible films, we first create two separate stl files for the encapsulating substrate and support substrate. These two files map to the film materials (e.g. agar and cellulose) and we generate G-code from these files using Slic3r. Upon printing, the temperature of each syringe is heated close to its material's glass transition temperature and extruded through the syringe at a target rate set by the firmware and G-code. The cooling system rapidly cools each layer of substrate to a solid state upon deposition, enabling layering of both materials to form the thin film. To date, we have run only preliminary tests for printing our materials using this method. We believe it offers considerable promise for desktop design and fabrication of transforming edible films.

Collaboration between CHI and Material/Food Science

Shape-changing interfaces based on material innovation is an emerging field in HCI. Beyond using non-edible materials that can change shape, stiffness, color, conductivity, and transparency, using edible materials provide new opportunities for HCI designers due to its low barriers to entry, high reproducibility, and safe consumption. In general, the design process is composed of three major steps. First, designers together with scientists predict the tangible outcome and analyze the theoretical feasibility. Second, scientists work closely with designers to test the material performance to develop a proof-of-concept design. They may re-adjust their goal based on the initial test results. Third, designers further improve the fabrication process and simulate the performance. Compared to conventional material-driven design, food material has low knowledge barrier and requires less hands-on training, enabling the high involvement of CHI designers in the whole process, from material discovery to the final design. The availability of the food materials will also provide other CHI researchers to enter into this research field easily, and reproduce previous design prototypes.

CONCLUSION

In this paper, we proposed a new concept - transformative appetite - that transforms 2D edible films to into 3D shapes by anisotropic swelling through cooking. Based on simulation using finite element analysis, a simplified geometry expansion model was built into a user interface, allowing users to create various design shapes, simulate transformation and fabricate transformable dishes. The underlying principles for more complex shape transformation were further applied to create innovative dining experience, enhancing the interactivity between food and cooking conditions, and between food and users.

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