The Design and 4d Printing of Epithelial Cell-Inspired Programmable Surface Geometry

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As a design research project, this paper aims to provide a novel surface geometry design and fabrication strategy. As the foundation, this paper discusses and investigates the deformation mechanism and geometric features of cellular epithelial tissues, especially the generation of the newly discovered scutoid shape. Subsequently, we utilize the mechanism to design and fabricate programmable physical surface geometry that can change shape autonomously based on external stimulation. We summarize the work we have conducted thus far into two aspects: First, inspired by the deformation mechanism of epithelial cells we propose a new design strategy for generating complex surface geometry from transformable individual units; Second, we also develop a new 4d printing method, which allows the surface geometry to be programmed on demand and to emulate the generative and bio-inspired design model analogically.

Keywords: *programmable material, 4d printing, bio-inspired design, epithelial cell, scutoid, surface design*

INTRODUCTION

Surface modeling and design in the digital environment has become a significant part of computational design and fabrication planning. Designers can efficiently obtain access to digital surface design toolkits, now readily available through online forums such as "Food4Rhino". Nevertheless, designers and makers still have fewer available methods for fabricating complex surface geometry. The repetitive operation of designing complex surface geometry is inevitable as designers often face more parameters and notation systems to optimize and organize the freeform surface morphology than conventional cubic architectural geometry. Additionally, we propose a bottom-up strategy for coordinating complex surface design that starts with local component-based rules and transformations to inflect a global change in surface curvature . This is in contrast to more traditional optimization methods that frequently privilege a top-down methodology where global surface change is organized into a family of non-standard discrete components post-facto.

The success of the surface design development process heavily depends on the design medium that the designers use. While the digital model helps to visualize the design intent, comparatively, it is reported (Sun. et al, 2014) that the physical model provides designers higher accuracy and acceptance in terms of spatial understanding and usability . Given the higher uncertainty and complex geometric property of freeform surface design, it is necessary to develop a new physical design media and shape-changing interface. This new interface can change surface geometry morphology based on the designer's intent and manual, analog input to facilitate a designer's spatial understanding. Various projects have explored and employed the ability of shape-changing interfaces in the domain of design. However, the biggest challenges of shape-changing design media lie in two aspects: First, most of the precedent works rely on electronic parts to power and control the shape, which limits a designer's degree of interaction while conducting real-time design activities and updates; Second, the possibility of an interactive design process is subject to the limited movement of a shape-changing interface since most such assemblies are implemented through the actuators' linear or rotary motion. Coelho. et al, 2011) In this case, the new shape-changing interface for surface geometry design proposed in this paper needs to satisfy two features: A, The changing shape should not be driven by any electrical actuator; B, the physical interface needs to be easily deformed and programmed to any degree of freedom.

In this paper, combining the two above expectations, we explore two methods as a new design foundation .

Our work focuses on the surface geometry bending mechanism. Specifically, we are inspired by the epithelial tissue's bending mechanism. Epithelial tissue that is constituted with tightly packed epithelial cells envelopes into complex cavities to cover the majority of the surface area of living being's bodies, including skin, organs, and blood vessels. Such features allow epithelial cells to deform and proliferate locally and adapt to different environmental conditions globally. This intriguing feature motivates us, as design researchers, to develop a novel design strategy that generates complex surface structures in both digital and physical surface geometry through the combination of individual units. Scientists (Gómez-Gálvez, et al, 2018) recently discovered that epithelial tissue's deformation capability is contributed to the emergence of scutoid geometry at the micro-scale. And scutoid is an ideal 3d package solution for a highly curved environment.(Mughal, A., et al. 2018) Scutoid, as three-dimensional geometry, bridges two parallel surfaces and is often described as a combination of the frustum and a prismatoid as it has a different number of edge segments on its basal surface and apical surface. One of this paper's targets is implementing the deformation process of epithelial tissue at a material scale and developing physical prototypes to implement the deformation. Then to eventually take the prototype as a design media to facilitate design activities.

By integrating the bio-inspired surface geometry bending mechanism, we aim to use smart material to fabricate the physical surface geometry that can change its shape autonomously based on external stimulation without any electric input element. Such work is implemented through 3 dimensionally printing with shape memory polymer. The long-term development of 3d printing technology has dramatically reduced the application threshold for designers. In recent years, many design practitioners and researchers utilize smart materials' characteristics such as shape memory further to expand the concept of 3D printing into 4D printing (Behl, M, and Lendlein, A, 2007,) . Our work in this paper focuses on taking advantage of the material behavior to execute the surface geometry bending process and how we can adequately fabricate such surface geometry.

RELATED WORK

There are related exploratory works that have been done in both trajectories recently

There is a lot of percent work in different fields that have been done and sets a solid foundation for our investigation. To be specific, in terms of using cell morphology for geometric modeling, Subramanian, et al. (2019) proposed a 3d space tiling method inspired featuring scutoid's geometric feature on its apical and basal surface. From the perspective of bio-inspired surface design, by investigating the biological principles in a micro-scale, Sabin and Jones (2008) investigated code-driven parametric design method, models, and tools to gain new insights into how nature deals with dynamics, environment, and feedback within cell and tissue structures, and in turn utilize those into architectural scale. Although the scutoid was discovered and termed in 2018, a few precedents work that links scutoid/epithelial cell with design and fabrication can still be found. (Tsikoliya, et al.2021) discussed architectural structure molding method that is based on differential growth of epithelial tissue. Inspired by epithelial tissue's deformation and the emergence of scutoid geometry, the authors proposed a continuity folds modeling approach and fabrication planning with concrete for architectural scale experiments. However, the deformability of epithelial cells can only be fully demonstrated over time. Instead, the work they proposed results in a set of static architectural elements, which we consider do not make full use of epithelial cells' deformability. Some other works paid attention to the cellular structure of epithelial cells. Due to scutoid's structural stability, Dhari, et al.(2021) proposes a 3D-printed Scutoids-inspired cellular structure for use in lightweight sandwich structure designs that copes compression loads. The structure was made of aluminum alloy and is reportedly to be able to absorb more energy than a regular compressive structure. The work scientifically demonstrates that, from a structural point of view, the bent epithelial tissue and scutoid shape are highly rational. Yet, the work leaves a blank space on scutoid fabrication with soft material. Teng, Jia and Sabin (2020) claimed a novel masonry shell system embedded with the geometric features of scutoid. Inspired by scutoids having different adjacent cells on different faces, all bricks in the mentioned masonry shell interlocked each other without external joints needed. The work took one step out in terms of using scutoid geometric features as a standing point of surface design.

As we are targeting to implement the deformation process at the material scale, we examined material and methods that can be potentially used to fabricate Epithelial cell-inspired Surface Geometry. Specifically, we evaluated precedent works of three-dimensional printing objects with active material and 4d printing process. In a lot of Tibbits 's work (2012,2014) , the material is pre-programmed and equipped with actuating abilities and reacting ability. It allows the material to self-deform over time when exposed to external stimulation and morphs into the desired 3d shape. Lee, A.Y., et al.(2017) comprehensively summarizes the fabrication method of reversibility of 3D-printed shape-memory materials such as depositing with additives or use multiple materials.

METHOD

Computer Simulation

We firstly investigate the deformation of epithelial cells thorough a scientific literature review. Referring to research in cell and molecular biology, (Gibson, et al. 2006. Lecuit , et al. 2007. Martin, et al. 2009. Kong, et al. (2017), we learned that the global deformation of the epithelial tissue is proceeded by the position rearrangement of individual epithelial cells in the tissue. We then computationally simulate the bending process within the tissues through a generative modeling methodology. The simulations demonstrate the emergence of scutoid geometrical shapes within the epithelial cells. We conclude that the cell rearrangement is achieved through cells revolving and contracting (Figure 1). These morphological transformations create a triangle face on the volume, transiting the extra edge on the apical surface to the basal surface through an extra vertex.

Our previous work (Teng, Jia and Sabin, 2020) has investigated that scutoid's extra edge segments on one of the surfaces merge into vertexes in the intermedia level to equalize the edge segment's number on another surface. We also discovered that epithelial tissue's curvature positively correlates to the length of the boundary between two adjacent epithelial cells as scutoid cells are generated through cells revolving and squeezing. Bending within the Epithelial tissue causes different motion tendencies on epithelial tissues' apical and basal surfaces (Figure 2). When the epithelial tissue is bent, the adjacent cell surfaces will squeeze each other where the curvature

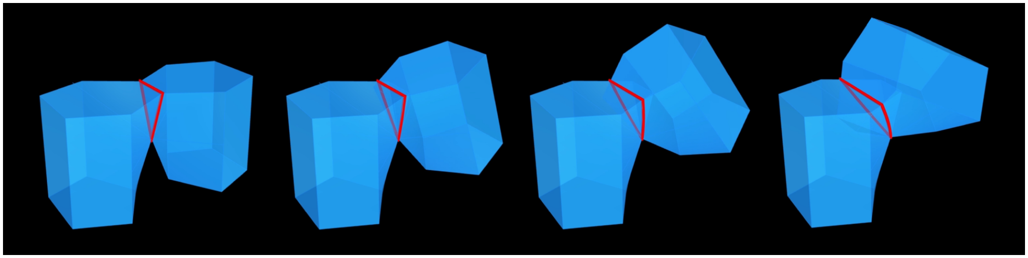


Figure 1
cell rearrangement is achieved through cells revolving and contracting

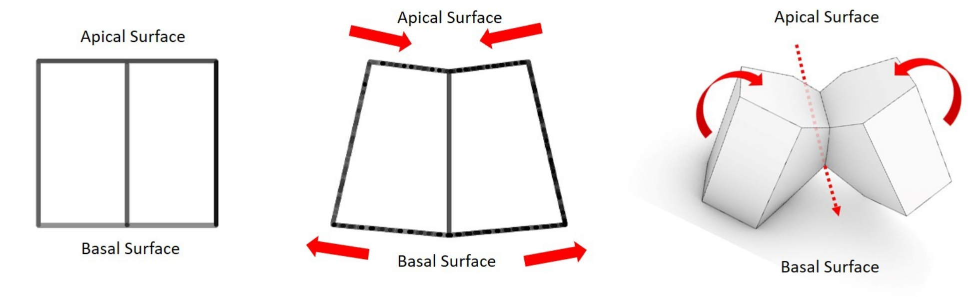


Figure 2
Two adjacent cells bent towards to apical surface. The apical and basal surface of each cell has a different motion tendency. left: a flat tissue constituted by two cells, middle: two cells tissue bent towards to apical surface from the side view. right: two cells tissue bent towards to apical surface in 3D.

is positive and separate where the curvature is negative. The geometric centers of adjacent cells' profiles move towards each other where the curvature is positive. The closer the two cells' geometric centers are, the greater the squeezing between the two cells is, resulting in a longer boundary line. In summary, the greater the curvature of the epithelial tissue, the longer the boundary between two adjacent cells at the curved position. Cells in highly curved global epithelial tissue deform along the apical-basal axis. The deformation process results in cells having different neighbors in their basal and apical surfaces.

Physical Prototype

Based on the above findings and geometric relationships, when designing a physical surface geometry with scutoid components embedded, we look into the dialectical relationhips between global surface geometry and local units. We hypothesized that if we can change the length of the boundaries between any pair of adjacent cells within a given model, we can then change the curvature of global surface geometry. Moreover, when the length of the boundary between any pair of adjacent cells is programmed, the global surface's overall morphology can be precisely controlled. The hypothesis is verified in a later context.

We identified two appropriate materials to be the most suitable deformable material through a series of material experiments: silicon and Shape Memory Polymer, as both materials are reversibly deformable and can translate the cells' behavior to a greater scale. In addition to the findings on the epithelial cells' geometric features that we discuss, the physical prototype and material studies should also follow the cell's geometric constraints. Study (Ruprecht, Jean-Francois, et al. 2017) investigated that cells compete for space under geometric constraints. The cell's three-dimensional morphology and packing within epithelial tissues is significantly impacted by geometric constraints. According to the literature, the geometric constraints include expansion force from the cytoskeleton and adhesion between cell membranes.

Based on these constraints, we further developed a set of programmable surface geometry prototypes to illustrate the global surface geometry deformation at a material scale using 3d printable shape memory polymer filament and silicon. The heat transfer of liquid-crystalline domains causes the shape memory effect. After the 3d printer heats the polymer to the isotropy state, the nozzle starts depositing the filament layers into the specified 3d shape. Polymer is initially programmed at this moment. As the material remains at a high temperature (temperature A), the printed 3d shape stays in its initial state A and remains soft. When the printing is done, and the 3d shape cools down to room temperature, it becomes firm. Following reheating the shape to temperature B, the shape becomes soft again. The designer can deform the printed 3d shape into state B on demand. After cooling down and changing the environmental temperature between temperature A and temperature B, designers obtained one object with two deformable morphologies at two different times. The forming of silicon in this project is fabricated through casting after we 3d print the formwork with PLA.

Aside from the digital simulation mentioned earlier, two types of deformable surface geometry are then designed and built for serving two purposes: First, the physical prototype verifies if scutoid cells will actually emerge at the local unit when the global surface curvature changes. Second, dialectically, the prototype also verifies if the global surface will be bent when the local units deform into scutoid cells. Both types of prototypes share a common design: To analogically translate the expansive force from the cells' cytoskeleton, we developed a set of cell units to be inserted into a constrained frame, which simulates the adhesion between cell membranes. The configuration constitutes a surface geometry while maintaining a dense packing of cells.(Figure 3)

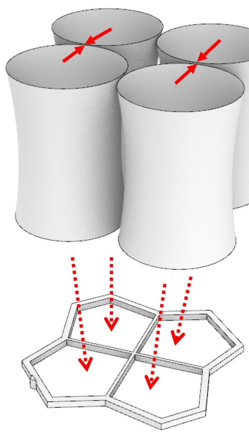


Figure 3
we developed a set of cell units to be inserted into a constrained frame

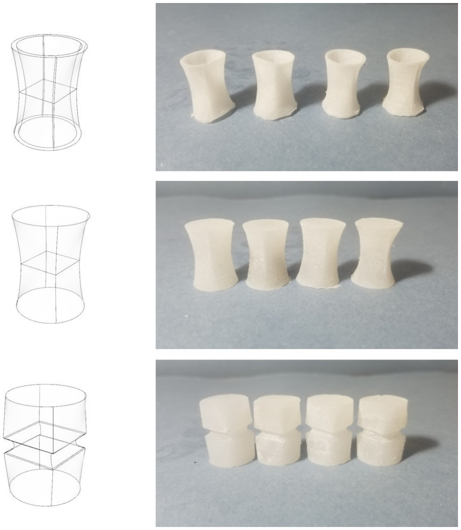


Figure 4
different type of
casted silicon unit

Figure 5
silicon unit inserted
into Shape Memory
Polymer constraint
frame.

The first prototype is generated by inserting cast silicon units into a 3d printed Shape Memory Polymer constraint frame. As active material, the Shape Memory Polymer, which represents the global surface geometry, is deformed according to environmental stimulation, the thermal environment, in this case. We designed and programmed the Shape Memory Polymer frame to stay flat as the initial state at temperature A and to bend towards the apical surface when the temperature reaches at B degree. The silicon units (Figure 5)representing the local units act as a passive deformation material and are tightly packed by the constraint frame. We then set the prototype in temperature A and have it stay flat and still(Figure 6). After gradually raising the temperature to B, the flat surface geometry starts bending towards its apical surface. Meanwhile, the local silicon units exhibited the expected behavior. As the global surface geometry prototype bends towards the apical surface, and all local silicon units revolve around the corresponding horizontal axis, adjacent local units squeeze each other through their boundaries. (Figure 6 and 7) The length of boundaries becomes longer when the globe curvature increases . Such local units' behavior generates the scutoid shapes. This process illustrates how the curvature change of the global surface geometry impacts local cell morphology.

In contrast, the constraint frame for the second surface geometry prototype is made by silicon representing the global surface, and all local cell units are 3d printed with SMP. We firstly 3d printed all SMP local units as regular frustums with its apical and basal surface flat at temperature A. We then programmed each SMP unit individually to deform into a scutoid shape at temperature B. Deforming units into scutoid cells means purposely changing the length of the common boundary between two adjacent units and the triangular face's size that transitions the polyline edge into a vertex to determine the expected curvature of the final global surface geometry at that unit's position. First, the SMP units are tightly packed into a global surface with the constraint frame and the surface prototype is placed in the thermal environment. Next, the SMP cell units actively deform from regular frustums into scutoid shapes with various sizes generated at the common boundary length or connection at the triangulated face. Thus, the prototype deformed from a flat surface geometry into a curved and programmed surface geometry. This prototype illustrates how local units impact global geometry deformation and morphology. □Figure 8□

To conclude with the above observations from the physical prototype experiment, in a surface geometry (epithelial tissue) constituted by smaller units (epithelial cells), the global surface and local unit's morphology influences each other. To activate such

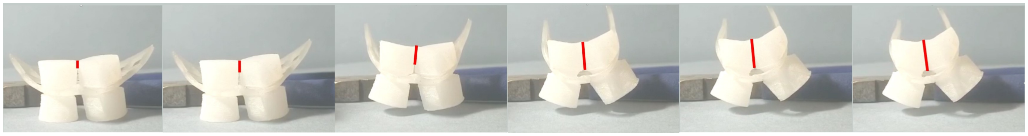


Figure 6
Two cell's tissue bent towards to apical surface, the length of the common boundary between two cells becomes longer when overall curvature increases. Photo taken from side view.

Figure 7
3d printed SMP active constraint frame inserted with silicon unit, when constraint frame bent towards to apical surface, all units deforms into scutoid. Photo taken from front view.

surface geometry, we either program the overall global surface curvature or program the individual units' morphology.

APPLICATION

The work we have completed thus far has illustrated how we combine the geometric features of epithelial cells with smart material additive manufacturing to achieve bioinspired programmable surface geometry. Importantly, this work leverages local transformations at the cell/component level to achieve global changes to surface curvature.

However, such programmable surface geometry is still not an ideal shape-changing interface for design applications. As a physical interface, interaction design and responsivitiy has not been emphasized in this latest set of experiments. As mentioned previously, the purpose of using a physical model in this design research is to demonstrate at the material level, a bottom-up strategy for bio-inspired complex surface design that leverages local component-based rules and transformations to inflect a global change in surface curvature . This construct also benefits the designer through an intuitive methodology that links responsive material interface with complex component-based surface design. We propose two ways that the bioinspired programmable surface geometry can interact with the designer: First, the designer interacts with the surface geometry by programming its target morphology. When a designer deliberates a complex surface design, it is easier for the designer to shape the desired morphology by manually stretching or bending the material assembly than by modifying it in a digital environment.

Second, we designed an embeddable flex sensor to attach to the physical surface geometry (Figure 9). When the designer shapes the surface on demand, the flex sensor, which consists of conductive ink, bends with the physical surface. The bending behavior forms a flexible potentiometer in which resistance changes upon deflection. (Figure 10) Higher curvature on the physical surface results in higher re-

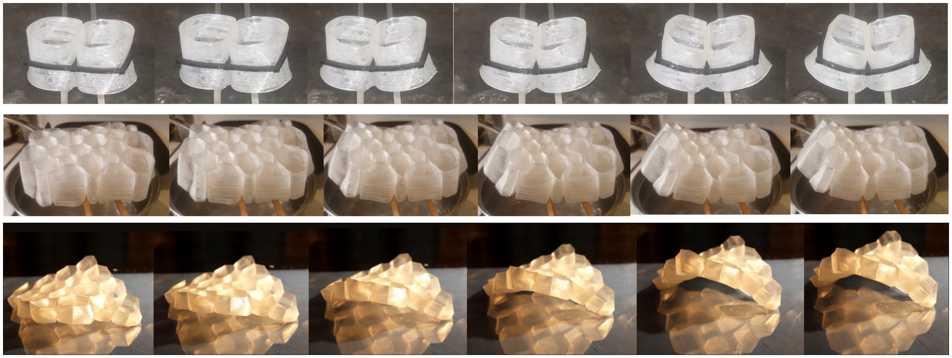


Figure 8
Upper: Two SMP cells tissue bent towards to apical surface. Two cells actively revolving and contracting towards each other results in constraint frame bent. Middle: SMP cells actively deform themselves into scutoids to bend globe surface geometry towards the apical surface. Lower: SMP cells actively deform themselves into scutoids to bend globe surface geometry towards the basal surface.

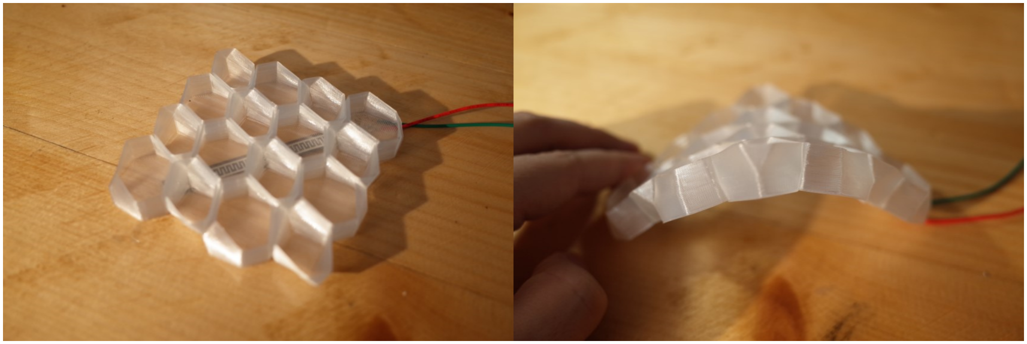
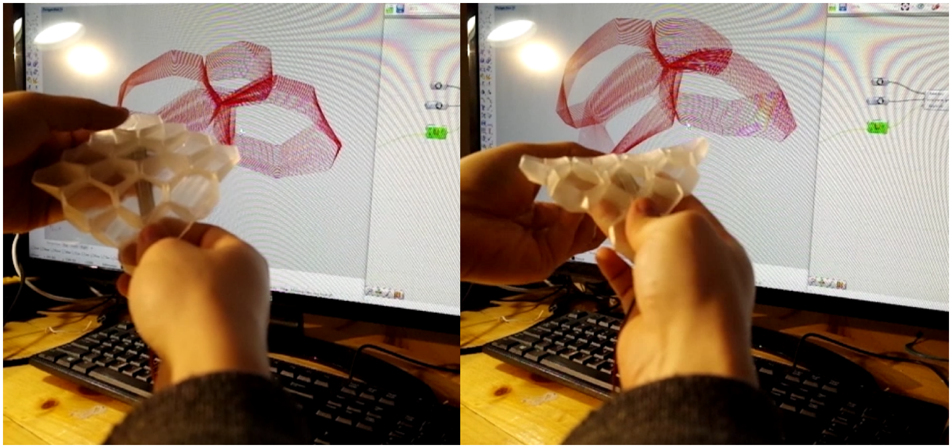


Figure 9
flex sensor attach to the back of physical surface geometry

Figure 10
The designer manually shapes the physical geometry, and the flex sensor captures the curvature data to digitize the surface.



sistance on the flex sensor . A microcontroller (Arduino) connects with the flex sensor and converts the resistance to curvature data in real time , then transmits data to computer modeling software (Rhino and Grasshopper) to digitize the physical surface.

The above two ways create a feedback loop that allows the designer to incorporate his/her design intent directly with the physical surface geometry. Adjustments to the morphology are immediately input as updated data in the digital modeling environment.

CONCLUSION

We have proposed a materially-based bottom-up strategy for coordinating complex surface design that starts with local component-based rules and transformations to inflect a global change in surface curvature . We have summarized the work thus far into two aspects: 1.) Inspired by the deformation mechanism of epithelial cells, we propose a new design strategy for generating complex surface geometry from transformable individual units; 2.) We developed a new 4d printing method, which allows the surface geometry to be programmed on demand and to emulate the generative and bio-inspired design model analogically.

In this paper, we outline the methods developed to prototype a bio-inspired programmable surface geometry as a design interface concept. We have successfully satisfied the two initial requirements that we proposed: 1.) We eliminated the electrical actuator, a commonly used driver in actuating a programmable surface to inflect changes to surface geometry. This is achieved by incorporating responsive 3d printed shape memory polymer and through a design methodology that leverages the deformation mechanism and geometric features of cellular epithelial tissues. We also developed a bottom-up design methodology to work with surface geometry that can be deformed and programmed to any degree of freedom, at local and global levels, by embedding scutoid geometric features. Beyond proposing the programmable surface geometry as a design interface, the work we have completed provides a novel and interactive strategy for designing surface geometry.

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