Non-uniform Kirigami Enhances Films Conformability

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Abstract. Developing films with great conformability has become a research hotspot in many fields. The conventional method to enhance conformability is to make the film thinner and more compliant, which usually compromises the strength of the structure. For example, developing functional medical bandages that can perfectly conform to the skin surface during cyclic bending of the joints is still a considerable challenge. In this paper, we propose a novel non-uniform kirigami to make the film achieve the same non-uniform auxetic (negative Poisson’s ratio) deformation as the skin around the joint area. By mapping the corresponding unit cells to the target surface, the surface can easily achieve the same deformation as the target skin without any alterations in its thickness or adhesion. As the obtained non-uniform kirigami film structure has the same deformation behavior as the target skin surface, the conformability of the structure can be guaranteed during the entire rotation process of the joints. Moreover, the proposed film is also expected to be used in novel biomaterials, such as smart bandages, skin scaffold, etc.

1. Introduction
Film structure is applied in many applications such as flexible electronics, soft robotics, medical bandages and wearable devices. In these applications, enhancing conformability of the film is a main design objective. Conventional method to enhance film conformability is to make the film thinner, however, which will compromise the strength of the film. Therefore, new method to enhance film conformability is important.

Reasonable topological design of film structures has been indicated to be an effective way to enhance film conformability and adhesion without changing the properties and thickness of the film. Kim et al reported several electronic systems constructed by circuit designs based on a ‘wavy’ structure [1], which could lead to conformal contact and adequate adhesion when laminated onto skin. Lou et al developed a wearable textile made up of core-shell yarn structures [2]. The core-shell yarns enhance the conformability of the textile and enable the textile to endure many different kinds of deformations. As a result, the textile can be attached to any location on the human body. Zhao et al reported a paradigm that enhances film adhesion by applying rational kirigami cuts to the film [3]. However, the skin around the joints of the human body usually undergoes auxetic deformation during the rotation of the joints, and the conformability of the film can still be improved by introducing negative Poisson’s ratio (NPR) structures.

In materials with stable isotropy, the allowable range of Poisson’s ratio (PR) values is between -1 and 0.5, but NPRs have hardly been observed in real materials. Lakes was probably the first researcher to produce an NPR structure and a re-entrant unit cell [4], which aroused other researchers’ interest in NPR structures. Graded designs of NPR and conventional PR units have been used to make programmable metamaterials with a certain target deformation [4,5]. To ensure that the film structure
has the same deformation behavior as the target skin, structure with a non-uniform PR (NUPR) distribution was introduced by Han et al. [6–8]. Han’s team proposed a non-uniform film structure composed of honeycomb unit cells with different interior angles. The proposed structure can achieve the same deformation as the target skin by mapping the corresponding unit cells to the film. However, the overall coverage ratio of this structure is extremely low, which can be a fatal disadvantage for products that require a high coverage ratio, such as wearable devices and medical bandages. Therefore, a new film structure with both a NUPR distribution and a high coverage ratio is of great significance.

In this paper, we demonstrate a new adhesive film based on the application of a kirigami structure with non-uniform auxetic deformation behavior. To analyse the deformation behavior of human skin during the rotation of joints, elongation (along the rotation direction) and expansion (perpendicular to the rotation direction) values of each subregion of the target skin were measured, which were used to calculate the strain and PR of each subregion during joint motion. The right elbow of a participant was selected as the target surface, and the proposed kirigami film structure was constructed by connecting unit cells with different PR values to mimic the complex NUPR distribution of the target skin. The PR value of each unit cell could be changed by changing the geometry of the cell’s rectangular cuts. Finite element analysis (FEA) was carried out to verify the functionality of the NUPR kirigami film structure. And the result indicated that the NUPR film structure has much better compatibility and conformability with the target skin than the solid film structure.

2. Material and method

2.1. Material
To enhance the conformability and highlight the role of the structure, Hei-cast 8400 (H&K Co., Ltd, Tokyo, Japan), a universal material was selected. This material could be considered as linear elastic at small deformation, with a Young’s modulus of 1.15 MPa and PR of 0.4.

2.2. Target surface scan and analysis
In this paper, part of a 28-year-old man’s elbow skin was selected as the target surface, with a total area of approximately 70×100 mm². Human skin has a complex geometric shape, especially when considering the differences between each individual; therefore, it is difficult to manually build a completely consistent digital model. To shorten the model generation time of the target surface and simplify the model generation process, 3D scanning was used to capture the geomaterial data of the target surface. An ArtecTM Space Spider (Artec Inc., Luxembourg) was used to conduct 3D scanning of the skin surface of the participant’s right elbow, as shown in figure 1. The resolution of this scanner is 0.03 mm. In addition, the handheld 3D scanner could obtain 7.5 frames of high-resolution 3D images per second, and the real-time fusion of these frames could reduce the complexity of post-processing.

Figure 1 shows the scanning results of the target surface. To facilitate measurement and data recording, a thin emulsion film with grids was pasted onto the target area. The initial result of the scan is a point cloud file, and the final surface models were regenerated by proper surface fitting. Normally, the non-uniform rational B-splines (NURBS) method is used to fit the surface [9]. For 3D NURBS with the order of \((p, q)\), the mathematical definition is given in equation (1):

\[
S(u, v) = \frac{\sum_{x=0}^{n} \sum_{y=0}^{m} N_{x,p}(u)N_{y,q}(v)w_{x,y}C_{xy}}{\sum_{x=0}^{n} \sum_{y=0}^{m} N_{x,p}(u)N_{y,q}(v)w_{x,y}}
\]

\(0 < u, v < 1\)

\(p \leq n; q \leq m\)

where \(n\) and \(m\) denote the number of control points in the directions of \(u\) and \(v\), and \(n\) and \(m\) must satisfy \(n \geq p, m \geq q\), which are the non-rational B-spline basis functions defined on the knot
vectors. $C_{x,y}$ are the coordinates of the control point, $w_{x,y}$ is the weight of the control point; in this article, $w_{x,y} = 1$. The fitted NURBS surface can be arbitrarily divided into smaller subregions.

**Figure 1.** 3D scanning of the participant’s right elbow: (a) shows the initial state of the elbow, (b) depicts the constructed computer aided design (CAD) model of the initial state skin area, (c) shows the target state of the bent elbow, and (d) is the constructed CAD model of the target state skin area.

To analyse the deformation of the target skin, the participant’s elbow extension state was set as the initial state, and the elbow bent to approximately 90° was set as the target state. The meshed emulsion film covered the skin, and a spider scanner was applied to record the three-dimensional model of the participant’s right elbow at the initial state and target state. Each subregion’s side length of the two states was measured and recorded based on NURBS interpolation, as suggested in figure 2. Poisson defines the PR as the ratio of the transverse strain ($e_t$) to the longitudinal strain ($e_l$) when the material is stretched elastically, that is, $\nu = -e_t/e_l$. In this paper, the strain and PR value of each subregion from the initial state to the target state could be calculated by equation (2) and equation (3), where $l_{int}$ represents the length of each side in the initial state, and $l_{def}$ represents the length of each side in the target state. In the formulas, every length is the actual length between two points on the surface, and the calculation of the strain and PR based on the average value of the side lengths of the subregions symmetrically has a certain error. This effect can be ignored when the area of the subregion is small enough. Through this method, the strain and PR distribution of the entire target area can be obtained.

$$
\varepsilon_{w,x} = \frac{(l^t_{def} + l^d_{def} - l^t_{int} - l^d_{int})}{l^t_{int} + l^d_{int}} \# (2)
$$
2.3. Unit Cell Analysis and Structural Design

To mimic the non-uniform deformation performance of the skin, the proposed kirigami film structure should be provided with a similar PR distribution as the target skin to ensure that there is no shear stress between the film structure and human skin during the rotation of the joint. To achieve a NUPR distribution, the basic strategy is to form an integrated structure with unit cells that have the same strain-PR performance as each subregion of skin. The unit cell shown in figure 3 can easily change the PR value to obtain a series of cells from an NPR to positive PR by just changing the length and width of the rectangular slit. To analyse the PR values of different unit cells with different cut lengths under different strains, FEA was conducted that accounted for geometric nonlinearity. In FEA, the Young’s modulus of the material was set as 1.15 MPa, the PR was 0.4, and the load and boundary conditions of the analysis are shown in figure 3. Each unit cell covered a skin area of 10×10 mm$^2$. By applying a displacement $Dis_X$ on the left boundary of the unit cell, the output displacement was analysed.

\[ \nu_{w,z} = - \frac{\left( t_{def}^l + t_{def}^r - t_{int}^l - t_{int}^r \right)}{\left( t_{def}^l + t_{def}^r - t_{int}^l - t_{int}^r \right)} \times \frac{\left( t_{int}^l + t_{int}^r \right)}{\left( t_{int}^l + t_{int}^r \right)} \]  \hspace{1cm} (3)

The strain and PR value of each unit cell could be calculated with equation (4) and equation (5).

\[ \varepsilon_{cell} = Dis_X / 10 \] \hspace{1cm} (4)

\[ \nu_{cell} = - Dis_Y / Dis_X \] \hspace{1cm} (5)

This paper used the form of "a-b" to represent units with different strain-PR relations; "a" represents the length of the rectangle in the X direction, and "b" represents the length of the rectangle in the Y-direction. This article analysed 14 sets of data from "0-1" to "0-7" and "1-7" to "7-7". As shown in figure 4, due to geometric nonlinearity during deformation, each unit cell has a different PR with the change of applied strain. The non-uniform structure was generated by assigning the corresponding unit cell to simulate the attributes of each skin subregion with the relation of ‘strain-PR-(a-b)’, letting $\varepsilon_{cell} = \varepsilon_{L,P}$ and $\nu_{cell} = \nu_{L,P}$. In this paper, the participant’s right elbow was selected as the target surface, and figure 5(b) shows the length of each edge for the subsurface $S_{(6,4)}$. With equation (2) and equation (3), we could obtain the strain ($\varepsilon_{6,4} = 0.2422$) and PR ($\nu_{6,4} = -0.4132$) of the subsurface $S_{(6,4)}$. Consequently, as shown in figure 5(d) and figure 5(e), the corresponding unit cell (with a similar strain and PR of $S_{(6,4)}$) ‘6-7’ was mapped to the position of $S_{(6,4)}$. According to this method, all subsurfaces were analysed from $S_{1,1}$ to $S_{10,7}$, and the corresponding unit cells were

![Figure 3. Geometry parameters and the load and boundary conditions for nonlinear FEA of the kirigami unit cell.](image)
mapped. By connecting the corresponding unit cells (the length of the connecting edge is the average of two adjacent unit cells), a NUPR structure was generated. The structure has a total of 7×10 unit cells, a total area of 70×100 mm$^2$, and a corresponding target surface area of approximately 70×100 mm$^2$.

![Figure 4](image)

**Figure 4.** The relation among strain, PR and ‘a-b’.

![Figure 5](image)

**Figure 5.** The construction process of the non-uniform structure. (a) The initial state, (b) is a subregion in the target surface. (c) The target state, (d) is a unit in the NUPR structure. (e) The layout of the NUPR structure is shown.

3. Simulations

Finite element simulations were carried out with the commercial software package ABAQUS/Standard to simulate the deformation process of the film structures during elbow rotation. Within ABAQUS, the C3D4 element was selected, the Young’s modulus of the material was 1.15 MPa, the PR was 0.4 and the thickness of the film was 1 mm. The model of the participant’s elbow was defined as a rigid body, and all its degrees of freedom were fixed in simulations. Then, the structure was covered in the target surface by applying displacement loads on two sides of the structure. In addition, the same operations were performed for the solid structure; then, the edges of the three structures were compared with the edge fit of the target surface. As shown in figure 6, the structure with a NUPR structure performs better. To quantitatively evaluate the fit of various structures to the target surface, we measured the distance between the midpoint of each unit on both sides of each structure and the corresponding point on the target surface and calculated the average. Table 1 shows the average distances and conformability (the reciprocal of the average distance) of the corresponding points at the edges of the structures and the target surface, which demonstrates that compared with solid film, the conformability of NUPR film was significantly enhanced.
Figure 6. Simulation-based conformability comparison of three different film structures: (a) top view, (b) left view and (c) right view.

Table 1. The average distance and the conformability of the edges of the three structures and the edges of the target surface.

| NUPR (mm) | Conformability (mm⁻¹) | Solid | Conformability (mm⁻¹) |
|-----------|-----------------------|-------|-----------------------|
| Left edge | 0.7527                | 1.33  | 0.9414                | 1.06                  |
| Right edge| 0.6606                | 1.51  | 1.7066                | 0.59                  |

4. Conclusions
This paper proposed a novel non-uniform kirigami film that could perform the similar non-uniform deformation behavior as the skin around a human joint during rotation. According to map the corresponding unit cells to the corresponding subregions, the generated film structure could mimic the deformation of the target skin. Consequently, there was much less stress between the film and skin, which would provide good attachment stability. The FEA results showed that the proposed NUPR film has much better conformability than solid film.

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