Human-Palm-Inspired Artificial Skin Material Enhances Operational Functionality of Hand Manipulation

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1. Introduction

Human skin is an organ that covers the entire human body. It plays various roles, such as protecting the human body, regulating body temperature, and sensing the external environment. For the human hand, the skin structure is extraordinarily important for enhancing hand functions. During hand manipulation, the palm skin directly contacts the object so that it acquires its information, and can firmly grasp the object with high adaptability. These skin functionalities are important for hand function as well as dexterous movement. Since the human hand is one of the most outstanding and familiar manipulators, various robotic hands have been developed to achieve its high functionality.[1–6] These robotic hands can grasp the object stably with various postures. However, as the next step, in-hand manipulation is now considered a key task of dexterous robotic hands, and many studies have been conducted for in-hand manipulation tasks.[7–11] Since the in-hand manipulation tasks are highly dynamic, being performed under more unstructured conditions, the robotic hands are required to have a functional skin structure that can both sense and firmly grasp the objects just as the human skin does. However, most of the research on functional skin has mainly focused on sensing capability, which leads to the development of various sensors in the shape of the skin. These sensors can sense pressure,[11,12] slip,[13,14] or temperature,[15] but cannot contribute to the grasping function.

There has been some research that dealt with a soft fingertip structure for a robotic manipulator to increase the grasping functionality.[16,17] The contact mechanism and the advantages and disadvantages of the soft fingertip have been discussed,[18,19] leading to some novel soft fingertip structures to be developed. (e.g., softness changeable fingertip[17] and fluid-filled soft cover[20]). While most of these structures mimic the stiffness characteristics of the human skin, they do not focus on the intrinsic mechanical functionality of the human skin structure. The first step in mimicking the intrinsic functionality of the human skin would be to understand how it contributes to the functionality of hand manipulation. It has been recognized that soft or human-like stiffness characteristics would help for adaptive grasping, but what features of the human skin structure play an important role and why it is advantageous for hand manipulation have never been studied. Specifically, for in-hand manipulation, the palm skin, which creates a more complex and various contact configurations, should be quantitatively analyzed to understand the underlying mechanisms of skin functionalities and to provide guidelines in the further development of functionally enhanced robotic hands.

Here we identified the advantages of human palm skin structure in dexterous manipulation and suggested a biomimetic skin structure that can enhance both stability and manipulability of the robotic hand system. Through the biomimetic design, we aimed to achieve and understand the underlying mechanism of the high functionality of the human palm skin.
The biomimetic skin structure is composed of three layers that correspond to the outer skin layer, subcutaneous fat layer, and inner muscle layer of the human skin structure. Each material was carefully selected to represent the intrinsic mechanical properties of each layer of the human skin structure. The advantages of the biomimetic skin structure were quantitatively verified in terms of stability and manipulability through experimental evaluation. The deformation characteristics and advantageous features of the proposed skin structure were analyzed using the finite element method (FEM) simulation. As a result, the biomimetic skin structure achieved both enhanced grasp stability and manipulability throughout wide grasp force condition, compared to conventional single-layer skin structures. Through the unique stiffness characteristics, which are highly compressible but tough in tensile direction, the biomimetic skin structure enlarges the contact area while firmly holding the object. In addition, we verified that the robotic hand with the biomimetic skin exhibits a much more enhanced grasping functionality and robustness against external disturbance.

2. Results and Discussion

2.1. Biomimetic Three-Layer Skin Structure

Analysis of the human skin structure and its characteristics was done prior to developing a functional skin structure. The macroscopic skin structure of the human hand, including the outer skin layer, subcutaneous fat layer, and inner muscle layer, is shown in Figure 1a. The subcutaneous fat layer is featured the most among these three layers because it is a complex of soft fat tissues and tough septa. The fat cells in the fat tissue contain a lot of big lipid droplets, resulting in low stiffness. The subcutaneous fat layer is much thicker than other skin areas, especially for palm skin. With the elastic outer skin layer, the entire structure acts like a water pocket, so it allows sufficient compressive deformation to adapt to the shape of an object during a grasp. At the same time, the tough septa hold the entire skin structure and prevent unwanted large tensile or shear deformation of skin structure by connecting the outer skin layer and stiff inner muscle layer. Consequently, the human skin structure has a unique asymmetric stiffness characteristic, which is highly compliant under the indentation and stiff against the tensile or shear direction. Furthermore, once the subcutaneous fat layer is fully deformed, the stiff muscle layer begins to act. Therefore, according to the indentation test shown in Figure 1b, the human skin shows increasing stiffness to the depth of the indentation.

To mimic these mechanical characteristics of the human skin, we propose a novel three-layer skin structure which is fabricated through the process shown in Figure 1c. For the outer skin layer and inner muscle layer, silicone materials were selected because they possess a similar stiffness and elasticity level to the corresponding layers of the human skin. For the subcutaneous fat layer, a porous latex structure was used to mimic its characteristics. The porous latex structure can represent the soft fat tissues and tough septa. Although the latex is basically much stiffer than the silicone materials, many pores in the porous latex structure significantly lower the overall stiffness under compression. These empty spaces in the porous structure act as the soft fat tissue of human skin. However, the tough latex walls between the air pockets hold the entire structure in the tensile direction, acting as the septa. Therefore, the mechanical behavior of the porous latex structure is comparable to that of the subcutaneous fat layer of the human skin structure. Based on this design strategy, the Ecoflex 0030 (Smooth-on, PA, USA) with 1 mm thickness and Ecoflex 0050 with 8 mm thickness were used for the outer skin layer and inner muscle layer, respectively. For the subcutaneous fat layer, a porous latex structure with 110 kg m$^{-3}$ rubber density, with 6 mm thickness, was used. A flexible adhesive (Sil-Poxy; Smooth-on, PA, USA)

![Figure 1](image-url)
was used for the adhesion between each layer. Figure S1 (Supporting Information) shows the entire skin structure used for the evaluation in this study. As shown in Figure 1d, the fabricated biomimetic skin structure has similar stiffness characteristics to the human skin structure. The thickness scale was controlled as half of the measured human skin, to be more compatible with robot hand application. Depending on the application, the overall stiffness trend or level could be modified through the methods described in the “Detailed Fabrication of Biomimetic Skin Structure” section in “Experimental Section.”

2.2. Mechanical Properties of Each Skin Structure Layer

For the analysis of the behavioral characteristics of the skin structure, it is of great significance to establish reliable material models that can accurately reflect the mechanical behavior of each constituent material. Polymer materials, such as silicone and latex, have inherent characteristics to recover their initial configuration after experiencing a large deformation without permanent damage or mechanical fracture. Therefore, linear elastic models cannot accurately depict their material behaviors. Nonlinear elastic behavior of hyperelastic (mostly incompressible) and hyperfoam (highly compressible) materials can be described by constitutive models for which the stress–strain relationship derives from a strain energy density function. A single test cannot reliably describe the mechanical behavior of materials in all deformation modes. Therefore, we used three different types of testing methods: uniaxial tension, planar tension, and uniaxial compression. The uniaxial tension test is one of the most basic tests to measure material properties such as Young modulus, maximum elongation, and Poisson’s ratio. The uniaxial compression test compliments the uniaxial tension test and is useful to measure a material’s asymmetric behavior in tension versus compression. The planar tension test is used to observe a material’s response to shear deformation, which is very important when characterizing hyperelastic materials. Figure 2 represents the measured nominal stress–strain curves of the Ecoflex series and porous latex specimens. The red line refers to porous latex materials, and the dotted line, dashed line, and solid line represent the Ecoflex 0010, Ecoflex 0030, and Ecoflex 0050, respectively. In Figure 2a,b, the results of uniaxial and planar tension tests show that the stiffness (slope of the curve) of porous latex is between Ecoflex 0010 and Ecoflex 0030. On the other hand, the stiffness of porous latex against compression has a much lower value, as shown in Figure 2c.

Since the number of Ecoflex indicates the shore hardness of the silicone material, it is natural that the higher number of Ecoflex shows higher stiffness. However, it is noteworthy that the porous latex structure showed interesting material properties compared with the Ecoflex series. As shown in Figure 2d, the porous latex structure shows the substantial asymmetric material response in tension versus compression compared with the Ecoflex series because of the many pores inside. The initial stiffness of the uniaxial and planar tension tests of porous latex show a similar softness with those of Ecoflex 0010 in a small strain range. However, the slopes of porous latex increase to similar or even higher numbers than the stiffness of Ecoflex 0030 for a large strain range. The compressive mechanical behavior, on the other hand, is very different from the tensile behavior. The curve of porous latex in Figure 2c shows that the porous latex structure is extremely soft to the compression direction, which is the typical compressive deformation of hyperfoam material. This asymmetric material behavior is explained in the schematics of Figure 2e and optical images in Figure 2f.

Although the detailed properties of hyperfoam material can be varied by controlling porosity, size of pore, and type of pore (open or closed), it has been well studied in previous research that the mechanical behavior during tension and compression has a typical stress–strain curve. First, in the tension test, the foam deforms in a linear, elastic manner as a result of the pore wall bending at a small strain range (T1 region on Figure 2d). As porous latex stretches further, the pore walls rotate and align, resulting in rising stiffness (T2 region on Figure 2d). The pores are substantially aligned at a tensile strain of about 0.3–0.4. During the compression, the stress–strain curve can be divided into three regions. The compression deformation mechanisms for small strain range are similar to the tensile mechanisms. The pores deform in a linear elastic manner with the pore wall bending at a small strain region (right after the O region). For the next region, a plateau of deformation with almost constant stress was caused by the elastic collapse of the pore wall columns (C1 region on Figure 2d). Finally, the rapid increase of the curve starts with the complete collapse of the pore wall (C2 region on Figure 2d). This implies that, at this stage, the elastic modulus of the structure is close to the pore wall modulus. Elastic modulus of bulk latex is generally a few MPa, which is much stiffer than the Ecoflex series. So, it can play exactly the same role as tough septa do. In addition, the role of many pores in porous latex matches with how fat tissue works in human skin. Consequently, it is shown that the porous latex structure behaves like the complex of soft fat tissue and tough septa, as the subcutaneous fat layer of the biomimetic skin structure.

2.3. Experimental Setup for Evaluation of the Proposed Skin Structure

The proposed biomimetic skin structure is aimed at enhancing the functionality of robotic prosthetic hands. Through quantitative evaluation, we showed that the proposed design could enhance stability and manipulability compared to the conventional single-layer skin structure. The stability and manipulability evaluation were conducted through the experimental setup shown in Figure 3. Although stability and manipulability are the terms that are initially defined in rigid robotic systems, they have often been modified for soft robotic systems. In the experimental setup, the skin structure can grasp objects with controlled grasping force while the response under the external wrench has been observed to determine the stability and manipulability. The maximum tolerable external wrench that the skin structure can hold an object against is considered an indicator of stability, while the smaller undesired displacement that a grasped object experienced under the same external wrench indicates better manipulability.

Since the palm skin makes a large and conformal contact area, the skin was designed in a flat, rectangular shape with
Figure 2. Nominal stress–nominal strain curves for Ecoflex series and porous latex. a) Uniaxial test. b) Planar tension test. c) Uniaxial compression test. d) Combined graph of uniaxial tension and compression test. e,f) Schematics of latex deformation and optical images during tension and compression test. C2, C1, O, T1, T2 represent each state of deformation of the porous latex.
15 mm thickness (Figure S1, Supporting Information) and the object was designed as a cylinder with a 50 mm diameter for the evaluation setup. The contact configuration between them is the power grasp, especially the medium wrap, which is the most versatile posture in the activities in daily living (ADL) tasks. Therefore, it is used as the representative configuration for the grasp condition. In addition, it is notable that, by using a cylindrical object, the circular contact shape (in cross-sectional view) is maintained regardless of the amount of grasp force, indentation depth, and rotation angle of the object under the external wrench. Therefore, the proposed evaluation setup simplifies the analysis since additional consideration on the changes in contact geometry is not needed.

As shown in Figure 3a, two skin structures were prepared to grasp the object with the controlled grasp force on both sides. The load cell (CSBA-20LS, Curiosity Technology Co., Ltd., Paju, Korea) monitored the grasp force in real time during the evaluation. The external torque was applied through the wire, which passes the top of the object with a z-shaped path. The translational forces were canceled out, and the pure torque is applied as the external wrench to the object. The amount of the torque was measured through a torque sensor (Nano 17, ATI Industrial Automation, NC, USA), while the motion data were measured by a motion capture system (Vicon Motion Systems Ltd., Oxford, UK).

The performance of single-layer structures was also evaluated to represent conventional skin structures as a comparison group. Each Ecoflex 0010, 0030, and 0050 single-layer skin structures show an increasing stiffness level. It is notable that the Ecoflex 0010 skin structure has the same stiffness level as the fabricated biomimetic skin structure under the 18.2 N grasp force. The thickness of the single-layer structures, 15 mm, is identical to that of the biomimetic skin structure. For the same surface condition, a pair of 0.5 mm thick Ecoflex 0010 silicone sheets were used as the cover sheet of all tested skin structures. One side of these silicone sheets was given a smooth surface by using the surface tension diffuser (SLIDE STD; Smooth-on, PA, USA), and the other side has a sticky surface for sufficient bonding force between the cover sheet and skin structure. The surface friction coefficient between the silicone sheet and object surface (the polished aluminum alloy (AL6061) surface taped by Kapton tape) was measured as around 4.0, under a 26 °C and 40% humidity condition. By using the same surface cover, all skin structures made of different materials have identical surface conditions. As the surface friction increases, the skin structure tends to hold the object more stable. However, by implementing the same surface condition, the structural benefits of each skin structure could be evaluated independently of the surface condition. The friction between the skin structure

Figure 3. Evaluation setup for the stability and manipulability of the skin structure. a) Device setup for the evaluation. b) Evaluation process using the evaluation setup. After setting the initial state with the controlled grasp force, the exerted torque was increased (stage 1) until the slip occurred (stage 2).
and ground was regulated identically small by using the sliding mechanism, which avoids direct contact between them (Figure S2, Supporting Information). The sliding mechanism is necessary to remove the effect of the uncontrolled holding force due to the friction between the skin structures and the ground.

Figure 3b represents the evaluation process. First, the moving plate pushed the skin structure to grasp the object. It grasps the object with a controlled grasp force by real-time monitoring of the load cell (initial state). Then, the external torque is exerted to the object by pulling the wire. As the external torque increases, the object starts to have an unwanted displacement, but still, it is grasped by the skin structure without slip (stage 1). As the torque overcomes the threshold that the skin structure can endure, a slip occurs between the object surface and skin structure, resulting in a failure to grasp (stage 2). As shown in Figure S3 (Supporting Information), the maximum tolerable external torque and the amount of displacement were measured through the evaluation process.

The maximum tolerable external torque and amount of displacement of the object when slip occurs are used for the stability index and manipulability index, respectively. For the normalized indices, the measured value of the Ecoflex 0010 single-layer skin structure was used as the reference. Consequently, the stability index “S” and manipulability index “M” were defined through Equations (1) and (2), respectively. $T_{\text{max}}$ represents the maximum tolerable external torque, and $\theta_{\text{max}}$ represents the amount of object displacement under the maximum tolerable external torque. The skin structure with high stability and high manipulability could effectively hold the object under large external disturbances and accurately manipulate the object with less position error. For example, the skin structure with a 1.2 stability index and 1.4 manipulability index could hold a 20% larger external torque with a 40% reduced displacement compared to the Ecoflex 0010 skin structure. In the case of dynamic manipulation, the manipulation power is transferred to the object from the robotic hands via the skin structure. Therefore, the skin structure with low stability has the limitation of manipulating power due to the escape of the object from the skin structure. Also, the amount of displacement leads to an additional position error due to the deformation of the skin so that the skin structure with low manipulability induces a larger position error during the manipulation.

$$S = \frac{T_{\text{max, target structure}}}{T_{\text{max, Ecoflex 0010}}}$$  \hspace{1cm} (1)

$$M = 2 - \frac{\theta_{\text{max, target structure}}/T_{\text{max, target structure}}}{\theta_{\text{max, Ecoflex 0010}}/T_{\text{max, Ecoflex 0010}}}$$  \hspace{1cm} (2)

### 2.4. Analysis on Stability and Manipulability

The evaluated stability and manipulability indices of the skin structures are shown in Figure 4. The evaluation was conducted under various grasp force conditions for each skin structure. Under the 18.2 N grasp force, the biomimetic skin structure has the same effective stiffness to the reference Ecoflex 0010 skin structure. Under this condition, the biomimetic skin structure shows a 1.1 stability index and 1.32 manipulability index, which indicates that it can hold the object under a 10% larger external wrench with a 32% reduced displacement of the object. This indicates that, through the biomimetic skin structure, we can achieve both enhanced stability and manipulability compared to the single-layer skin structure with the same effective stiffness level.

When comparing the single-layer structures, there is a trade-off relationship between the manipulability and stability. As shown in Figure 4a, the stiffest material, the Ecoflex 0050, shows the highest manipulability among all the skin structures. However, the stability of Ecoflex 0050 is the lowest, as shown in Figure 4b. This trade-off becomes more significant in a low grasp force condition. This phenomenon could be explained by Persson’s rubber friction model, which shows the relationship between the surface friction and stiffness of the rubber material.[19,31,34] According to this model, the surface friction is lower for the stiff rubber material, even though the other surface conditions are identical. In addition, this model becomes dominant for the low contact force condition.[35] Therefore, as the stiffness becomes higher or the grasp force becomes lower, the surface friction of the skin structure becomes lower, so that the stability decreases. Consequently, adjusting the stiffness level of the skin structure results in a loss of the other index, only improving either stability or manipulability. Although low grasp force is the condition that causes low stability, it is inevitable for the in-hand manipulation tasks since the tight grasping force should be released first to change its posture during transition or reposition. This can easily cause the object to be shaken or dropped off. Therefore, an intrinsic functionality under the low grasp force condition is necessary to conduct the dynamic in-hand manipulation tasks effectively.

In contrast to the single-layer skin structures, the proposed biomimetic skin structure shows both enhanced stability and manipulability. Specifically, the stability of the low grasp force condition is increased remarkably. Since the biomimetic skin structure has unique stiffness characteristics that have a lower stiffness level for shallow indentation, the effective stiffness of the skin structure decreases as the grasp force decreases. Therefore, it grasps the object with a softer structure, which leads to increased stability. Simultaneously, it shows a high manipulability level, regardless of the grasp force. Like a highly compliant mattress, the porous latex layer allows the object to be immersed inside the skin structure but does not allow for twisting or escape of the object. Under the 5 N grasp force condition, the biomimetic skin structure could endure a 27% larger external torque compared to the Ecoflex 0010 single-layer skin structure, while allowing a 34% reduced displacement of the object.

Figure 4c represents the resulting functionality map of the skin structures. In summary, the conventional single-layer skin structures have a trade-off relationship between stability and manipulability. With an increased stiffness level, the manipulability increases, but the stability decreases. These trends become severe for the low grasp force, where the functionality of the skin structure becomes more important. However, we can increase both stability and manipulability simultaneously by applying the biomimetic design. Again, it is notable that these advantages become more significant for the low grasp force condition.
2.5. Characteristics of the Biomimetic Skin Structure via FEM Simulation

Ecoflex series and porous latex structures were modeled by determining the appropriate strain energy density functions based on the measured material properties to implement into the FEM simulation. The FEM simulation was conducted as the same procedure of experimental evaluation, and the advantageous features of the biomimetic skin structure were discovered quantitatively. The maximum tolerable torque and maximum angle just before slip were used to compare the performance of the skin structures. For the analysis, the initial grasp force of 18.2 N and torque were applied to each skin structure model the same as the experimental evaluation.

Figure 5a, b represents the evaluation for the biomimetic skin structure, and the evaluation of single-layer skin structures are shown in Figure S4 (Supporting Information). Details of the simulation modeling and validation process can be found in Notes S4–S8 (Supporting Information).

Figure 5c presents the contact area of each skin model after the same grasp force was applied (18.2 N). The biomimetic design shows an even larger contact area than that of Ecoflex 0010 due to the large deformation of porous latex. It is notable that those two skin structures have identical indentation depth since the biomimetic skin structure is designed to have the same effective stiffness under an 18.2 N condition. A large contact area helps the skin firmly hold the object. As can be seen from the simulation results of inset figures, most of the deformation in the biomimetic design structure occurred at the porous latex layer. The important point to note is the effect of the high tensile stiffness of porous latex. The relatively strong tensile properties of the porous latex prevent the skin structure from distortion when torque is applied. In order to analyze how the high tensile stiffness influences the stability of the biomimetic structure, a simulation validation was performed with the latex hyperfoam model, which is modeled by using only uniaxial compression test data. The hyperfoam model with only uniaxial compression data approximates its tensile behavior based on the compressive test data, which leads to low stiffness similar to the compressive behavior. This model was compared with the original biomimetic skin structure model shown in Figure 5d. As shown in Figure 5e, the simulation modeled by only compression test data resulted in a wrinkle as the applied torque was increased. When the upper part of the structure receives torque, it is pushed to the right, and at the same time, the latex is stretched by the inner muscle layer and outer skin layer. With low tensile stiffness, the latex fails to withstand this stress, resulting in a wrinkle of the skin surface.
Figure 5f shows the maximum tolerable torque and angle just before the slip occurred. Just like in the experimental evaluation, the proposed biomimetic skin structure shows an increased maximum tolerable torque, leading to higher stability. Displacement of the object was also relatively reduced so that higher manipulability can be achieved. However, for the case that a wrinkle occurred due to the absence of the high tensile stiffness of the porous latex structure, the performance of the biomimetic skin structure decreased to a similar level of single-layer skin structure made of Ecoflex 0030. Consequently, it is proven that a higher tensile stiffness of latex improves the stability and manipulability of biomimetic skin structure.

Similarly, we also found large buckling of Ecoflex 0010 under high grasp force and torque. Due to the softness of Ecoflex 0010, the structure cannot withstand external torque, so buckling of the entire structure was observed, as shown in Figure 5g. These phenomena have a significant influence on the durability of artificial skin. The occurrence of buckling and wrinkles on the simulation has a similar mechanism of blistering and peeling of actual human skin. Repeated external shear force can cause a fracture of the skin layer or delamination between the skin layers. In the same manner, if wrinkles in the skin structure repeatedly occur due to external force, the skin will lose its functionality. Therefore, the stiff inner muscle layer and tensile strength of the porous latex structure are important not only.
for the functionality but also for the durability against repeated deformation.

### 2.6. Biomimetic Functional Skin Structure Integration

Figure 6 shows a prosthetic hand with the proposed biomimetic skin structure. By applying the proposed design, the functional skin structure was integrated as the palm skin structure of the prosthetic hand. As shown in Figure 6a, the skin structure has a realistic surface curvature of human skin, including the crease, created with 3D scan data and a 3D printed mold. We verified that the advantages of biomimetic skin structure are derived from the proposed three-layer configuration and unique stiffness characteristics. Therefore, it can be applicable to various systems by fabricating desired shapes while maintaining its key characteristics. As shown in Figure 6b, the applied skin structure has the outer skin layer and inner muscle layer made of silicone material, and the subcutaneous fat layer made of porous latex structure. Detailed configuration is described in Note S10 and Table S6 (Supporting Information).

With this prosthetic hand system, we grasped a smartphone (Samsung Galaxy S6) with the four fingers and palm skin structure (four finger–palm grasp, Figure 6c). Most users touch their smartphone screen using their thumb while holding it with palm skin and four fingers, and the grasping posture using palm skin instead of the thumb is commonly required during in-hand manipulation.[36] The target hand was originally designed to grasp using the four fingers and thumb. Therefore, it has one degree of freedom (DOF) for each finger (fixed distal interphalangeal (DIP) joint angle and coupled proximal interphalangeal (PIP) and metacarpophalangeal (MCP) joint movement). Since the in-hand manipulation tasks mostly require enough DOF for its dexterous movement,[9,37] it was difficult to implement the in-hand manipulation tasks with the limited DOF of the target hand. However, by applying the biomimetic skin structure, the prosthetic hand is able to grasp the smartphone via four finger–palm grasp posture, as shown in Figure 6d.

**Figure 6.** Demonstration of the biomimetic skin structure with conventional prosthetic hands. a) Top view of the prosthetic hand system. The surface has a realistic shape of the human, including the crease based on the 3D scan data. b) Side view of the prosthetic hand system. The skin structure includes the outer skin layer, subcutaneous fat layer, and inner muscle layer. c) The posture that the prosthetic hand grasped the smartphone (Samsung Galaxy S6) via four finger–palm grasp. The gripper, including the torque sensor, gripped the top of the smartphone and the external torque was applied via this gripper. d) Measured maximum tolerable torque for both Ecoflex 0010 single-layer skin structure and biomimetic three-layer skin structure, under the target posture. e) The deformation characteristics of the biomimetic skin structure (hypothenar side). f) The deformation characteristics of the Ecoflex 0010 single-layer skin structure (hypothenar side). The skin structure was pushed out due to the pushing force form the object.
Figure 6c and Movie S1 (Supporting Information). The grasp showed strong robustness even when the prosthetic hand was shaken to give a disturbance. However, in the case of the prosthetic hand with the conventional single-layer skin structure, it could not effectively hold the smartphone. For comparison, the Ecoflex 0010 single-layer skin structure was also fabricated and had an identical shape and dimensions to the biomimetic skin structure. The surface condition was also made identical by using the same material for the surface layer (1 mm thick Ecoflex 0010 silicone with surface tension diffuser). The grasp with a single-layer skin structure frequently failed. Even though the skin structure succeeded in holding the smartphone by chance, the smartphone tended to pop out after a few seconds. In some trials, it could grasp the smartphone without popping out, but the grasp easily failed under the small disturbance.

For quantitative analysis, we applied the torque to the grasped phone via the gripper that includes the torque sensor. For both biomimetic skin structure and Ecoflex 0010 single-layer skin structure, the maximum tolerable torque was measured. The evaluation process is shown in Movie S2 (Supporting Information). As shown in Figure 6d, the biomimetic skin structure shows a 47% higher maximum tolerable torque compared to the conventional single-layer skin structure. It is a significant improvement, which is even larger than the difference shown in the previous experiments and simulation. Figure 6e,f explains the reasons for this significant difference. As shown in Figure 6e, the biomimetic skin structure adaptively deforms toward the surface of the object. As seen through the FEM simulation, the biomimetic skin structure provides a sufficient contact area to the object and generates the grasping force via the friction on the surface. At the same time, the entire skin structure can hold the object stably due to the strong tensile stiffness of the porous latex layer and the support of the base muscle layer. In contrast to the stable grasp posture of the biomimetic skin structure, the single-layer skin structure shows low functionalities as expected. Since the Ecoflex 0010 skin structure is sufficiently soft, it also deforms toward the surface of the object. However, as shown in Figure 6f, the entire skin structure was pushed out due to the force from the object, like the wrinkle or buckling that occurred during the experimental evaluation and simulation as shown in Figure 5e–g. Therefore, even though the grasp succeeded at the initial stage, the soft single-layer skin structure keeps being pushed out due to the force from the object. The contact region between the object and skin structure is also moved outside. Consequently, the object pops out from the skin structure. This phenomenon could be alleviated by using a stiffer material for the skin structure, but it would then decrease the stability.

3. Conclusion

We developed a biomimetic skin structure that consists of three layers that represent the outer skin, subcutaneous fat layer, and muscle layer to enhance the stability and manipulability of the conventional robotic hand system. Due to the asymmetric mechanical behavior of the porous latex layer used as the subcutaneous fat layer, the entire biomimetic skin structure has unique stiffness characteristics which have low stiffness under the compression and high resistibility regarding the distortion of the skin structure. To validate the functionality of skin structures, we newly defined two indices representing stability and manipulability based on the novel evaluation platform.

Through a quantitative evaluation of the stability and manipulability of the skin structure throughout the wide grasp force range, it was shown that the proposed design has both enhanced stability and manipulability compared to the conventional single-layer skin structures. The deformation characteristics and advantageous features of the proposed skin structure were analyzed using the simulation. The low stiffness regarding the compression increases the contact area and contributes to high stability. The decreasing stiffness characteristic at the low grasp force particularly contributes to the stability in low grasp force condition. The high stiffness in a tensile direction prevents the distortion of the skin structure, so that contributes to high manipulability. Furthermore, a higher tensile stiffness of latex improves not only the functionality of skin structure but also the durability against repeated deformation by preventing unwanted deformation such as wrinkles and buckling. It is notable that the surface condition that we used for the evaluation is not limited to a specific case. Since the governing mechanism of the biomimetic skin structure came out from the structural characteristics, the advantages of the biomimetic skin structure would remain for various surface conditions.

Based on the analysis of the deform characteristics and advantageous features of the proposed skin structure, the stiffness level or shape of the proposed skin structure is adjustable depending on various applications, such as prosthetic hands or robotic grippers. In addition, since the advantages of the proposed design come from the mechanical characteristics of the skin structure, the outer skin layer or the subcutaneous fat layer could be replaced with a sensor structure with similar mechanical properties. In further studies, the biomimetic skin structure with sensory function could achieve both sensory function and enhancement of functionality. Consequently, the proposed novel biomimetic skin structure design will advance the conventional robotic hand system toward challenging manipulation tasks.

4. Experimental Section

Detailed Fabrication of Biomimetic Skin Structure: The fabrication of the biomimetic skin structure starts with selecting proper materials based on the application. Notably, the rubber density level of the porous latex structure is highly related to the stiffness level of the entire structure, and the thickness of the porous latex layer is highly related to the point in the stress–strain curve where the stiffness curve begins to increase. The outer and inner silicone layers were cured separately and bonded to the latex layer afterward since the chemical characteristic of the latex inhibits the curing of the silicone, and the uncured liquid silicone material tends to fill in the pores in the porous latex structure. Based on the application, each layer can be designed in the desired shape via a customized molding process and latex cutting. For the adhesion, a flexible adhesive, Sil-Poxy (Smooth-on, PA, USA) was applied to the surface of each layer. During the bonding process, a moderate pressure (of about 5 kPa for the structure described in this paper) was applied to help bonding.

Characterization of Stiffness Characteristics of the Skin Structures: The indentation method was used to measure the stiffness characteristics of the human and fabricated skin structures. As shown in Figure S12a (Supporting Information), an indenter with a conic tip was used for the
measurement. The load cell (Honeywell model-13, Honeywell International Inc., NJ, USA) was placed inside the indenter so that the indentation load was measured and the motion capture system (Vicon Motion Systems Ltd., Oxford, UK) simultaneously tracked the motion of the indenter to measure the indentation depth. By using the indentation load and the indentation depth data, the stiffness characteristics were identified.

**Mechanical Testing of Skin Materials**: Each sample was tested at a temperature of 20 °C (ambient room temperature). The tensile test of hyperelastic and hyperfoam specimens was conducted in the strain range of 0 to ~100%, which can cover the deformation range of the human skin. For an engineering analysis, it may be more advantageous to have precise stress–strain measurements in the range of interest rather than to study the strain at failure. For the compression test, the samples were compressed to a strain of 0.5–0.8, which were pressed until nominal stress reached around 0.15 MPa. To reduce the Mullins effect, a cyclic test was repeated immediately three times, and on the fourth cycle, load-deflection data was recorded. The strain data were carefully checked through digital image correlation (DIC) for potential debonding or slippage at the rubber metal interfaces. A fine speckle pattern was applied to the specimen surface prior to testing. Through observation, it was confirmed that the total extension measured by the universal testing machine (UTM) was accurate with the value measured by DIC when the grip bonds the specimen well. Details of mechanical testing can be found in the Notes S2 and S3 (Supporting Information).

**Finite Element Method Simulation Modeling**: The FEM simulation was performed to verify the experimental results. The hyperelastic[47–54] and hyperfoam[55,56] models for each skin layer were directly implemented in the ABAQUS v 6.14-3[57] with four-node plane stress elements (CPS4R) (see Note S4 and S5 for details). Two validation simulations (tensile and indentation testing simulations) were conducted in advance to check whether the models were implemented properly (see Notes S6 and S7 in the Supporting Information for details). The functionality evaluation simulation was conducted with two steps: the indentation step and rotation step. The indentation force was applied to the skin structure, and then the object maintained its position. The object was modeled as a rigid body. 5 and 18.2 N were selected as a representative indentation force among the experiment conditions. At the following step, torque was applied until slip occurred. The friction of the contacted surface was followed by the Persson model[58,59,60] while the bottom surface was set to be friction free.

**Detailed Evaluation Procedure of Stability and Manipulability**: With the evaluation setup described in Figure 3, the functionality of the skin structures was quantitatively evaluated for stability and manipulability. A target pair of skin structures were mounted on the steel plates facing each other, and an object was grasped via the skin structures by moving the plate manually using the handle. The relative position of the object to the skin structures was carefully controlled as the position avoided translational force. Due to the viscoelastic characteristics of the skin structure, the grasp force, monitored via load cell, tends to decrease until it reaches the steady state. Therefore, after grasping the object, the grasp force was monitored and adjusted again to match with the target grasp force until the force decrease rate was less than 0.01 N s⁻¹.

Figure S3 (Supporting Information) shows an example of the data from the evaluation. Each evaluation test was conducted seven times. The maximum tolerable torque was determined as the point that the graph trend started to change from static friction (grasped) to dynamic friction (slip). Among the seven trials, the two outliers were rejected through statistical analysis. In order to find the two most outliers, the z-scores of each trial were calculated using the value of maximum tolerable torque and ratio between the maximum tolerable torque and displacement angle at that moment. The z-scores about these two values were separately calculated, and the absolute values of the z-scores were added together to represent the overall z-score about the single measurement trial. Since the z-score is the normalized deviation of the data from the average of the data set, both two indices could be evenly handled together to find outliers. With the calculated z-score, the two most abnormal were sequentially rejected, and the remaining five trials were used for the evaluation data for each condition.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords**

artificial skin, biomimetic, grasping, robotic hand, soft material

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