Ajisai: A Structure That Matches the Relationship Between Force and Color to Human Perception

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***Abstract*—Humans find it difficult to perceive visually the level of force exerted on an object by a robot operating with positional control. According to research, humans perceive colors in terms of weight following the order of yellow, green, blue, and red, clockwise on the hue circle. We believe that by developing a structure that changes colors in this specific order, we can achieve visual force transmission that aligns with the relationship between force and color as perceived by humans. In this letter, we used the photoelasticity of an anisotropic transparent material, which changes color depending on the applied force when sandwiched between two polarizing plates. The material is dumbbell shaped, which ensures equalization of the applied force. Based on this, we have developed a structure called Ajisai, which is powered by artificial muscles and whose colors change in response to applied force to match human perception.**

***Index Terms*—Force control, human-centered robotics, human-robot collaboration, soft robot materials and design.**

I. Introduction

HUMANS naturally adjust the way they hold objects based on their weight. Light objects are held lightly, while heavy objects are held firmly. Fragile objects are handled gently, whereas hard objects are held firmly. This is because humans move by unconsciously controlling both the force and position of their bodies to suit their intentions, owing to their body's structural characteristics. Consequently, as shown in the human figure in Fig. 1(a), the interaction between a human and an object, including whether the object is heavy or light, can be partially inferred from observable differences in gestures. Therefore, humans can collaborate in various environments. However, most general industrial robots and machines driven by electric motors or hydraulic pistons are operated using position control, and it is difficult to observe and estimate the object or content of the work from the robot's actions, as shown in the robot figure in Fig. 1(a). This situation is similar to that of a pantomime in which humans hold a light object as if it were heavy.

There is a growing interest in using machines and robots in domains such as labor, daily life, and medical care to replace human tasks, and robots and humans are expected to coexist and collaborate in the future. Therefore, it is crucial to ensure smooth and safe human-machine interactions. Recently, soft and soft-material robots have been investigated for flexible adaptation to various external environments.

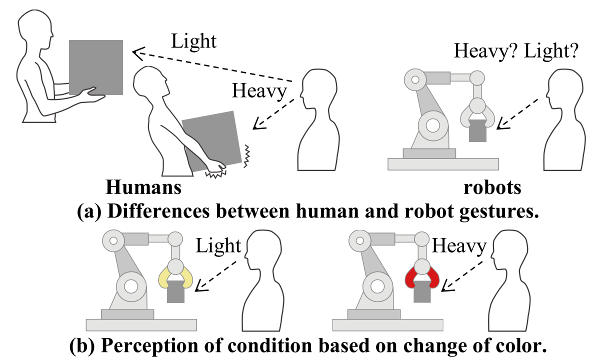

Fig. 1. Current and ideal state of condition perception.

For example, an insect-tarsus-inspired soft gripper with soft adhesive pads has been developed, enabling the grasping of complex, soft, deformable, and brittle objects that were previously challenging to handle using rigid or soft grippers [1]. A gripper equipped with a jamming mechanism that uses the density change of the enclosed powder, which can switch between the soft and hard states, allowing it to accommodate position errors and shape variations in the object. It is expected to be applied to robot arms for life support [2]. A soft gripper that uses 3D printing to create a soft mesh structure and uses a vacuum system to grip objects can be easily customized for prototyping and is expected to be used for various applications such as food manufacturing, in-house farming, and household chores [3]. A soft robot embedded in an organic ionic liquid-based conductive ink can sense its motion, pressure, touch, and temperature when touching an object [4]. Although these soft structures can passively generate movements that match the object, it is not possible to explicitly determine the state of the object from the outside. In other words, people cannot instantly and visually determine whether an object held by a robot is heavy or light. Considering the coexistence and collaboration between humans and robots, the status of a robot should be readable visually and explicitly based on its appearance. For example, the heavier the object to be grasped, the larger the arm part that expands, which is visualized as a force hump. This soft robot is made of silicon, powered by air, and is added to a normal robotic arm [5].

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In this study, we selected color as an element that changes the appearance of machines and robots and investigated a method for visually identifying their state based on color without using external electrical energy. For example, in the case of a robot hand, whether the object to be grasped is heavy or light, hard or soft, can be indicated by a change in the color of the hand itself. Instead of sensing the state of the object and displaying a numerical value or changing the appearance of the robot by changing the motion itself, the color of the robot itself can be changed passively. The robot does not need to use external electrical energy; thus, it is effective even in environments where no power source is available.

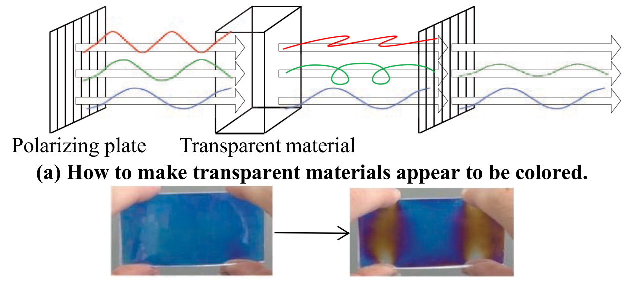
The following are the previous studies on color change according to the state of an object: When a mechanochromic fluorenylidene-acridane film generated by vacuum evaporation is mechanically stimulated, the molecular structure is deformed, and the film changes color from yellow to green [6]. Perovskite nanosheet hydrogels with mechanochromic structural colors instantly change from long-wavelength orange to short-wavelength blue when a force is applied [7]. Thermochromic pigment-based thermosensitive visual-tactile sensors with three threshold values undergo a color transformation to blue, orange, and black [8]. Although these studies focus on color change induced by external stimuli, the mechanical properties may be insufficient because the stages of change are small, and they are not designed for adaptation to machines or robots. Previously, we developed the soft robotic hand, which expresses external forces such as color that can steplessly change and deformation as a feasibility study [9]. We have clarified the feasibility of expressing external forces in color by using the color change caused by the photoelasticity of ordinary polymer materials.

In this study, our goal is to facilitate a more intuitive visual understanding of force by using colors, as shown in the conceptual diagram in Fig. 1(b), which could not be achieved in the previous study. Using this system, we aim to improve the interaction between humans and machines or robots. Specifically, we will focus on developing a mechanical element named "Ajisai" that can represent colors corresponding to the forces generated by machines, robots, actuators, and similar entities and the feeling of lightness or heaviness that humans associate with each color and develop a robotic hand that applied it.

II. Relationship Between Photoelasticity and the Lightness and Heaviness of Color

A. Photoelasticity

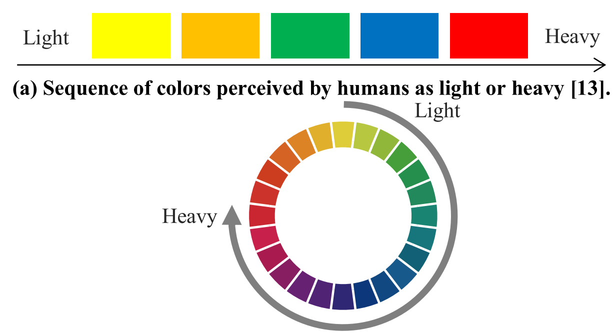
We applied photoelasticity to visualize these forces. Photoelasticity is a technique that is used to analyze stress in an object and has been used in the structural design of machines, structures, and components [10], [11]. As shown in Fig. 2(a), when polarized light enters a transparent polymer material with anisotropy, the polarization state alters based on the light wavelength, resulting in the observation of colors that are enhanced by those that can traverse the polarizing plate. When an external force is applied to a transparent material, the molecular arrangement within the material undergoes a change solely in



(a) How to make transparent materials appear to be colored.

(b) Photoelasticity

Fig. 2. Mechanisms of polarization and photoelasticity.



(a) Sequence of colors perceived by humans as light or heavy [13].

(b) Correspondence between heaviness of color and the Munsell color system.

Fig. 3. Sequence of human perception of heaviness of color and its correspondence to hue rings.

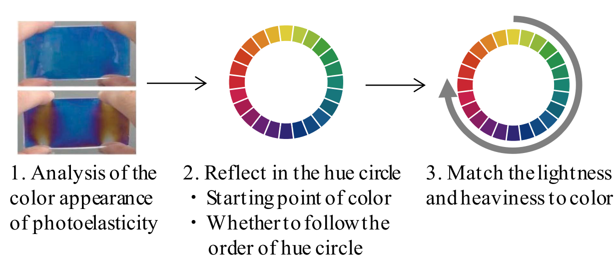


Fig. 4. Process to match the lightness and heaviness of the color.

that affected region, leading to a variation in the coloration. This phenomenon is referred to as photoelasticity (Fig. 2(b)).

B. Lightness and Heaviness of Color

Humans possess a sense of lightness or heaviness associated. Pinkerton et al. [12] discovered that the perceived heaviness followed a sequence: yellow, orange, green, blue, and red, as shown in Fig. 3(a). This sequence aligns with the hue rings of the Munsell color system used for color identification in ISO and JIS. The sequence of heaviness is clockwise, starting with yellow and ending with red, as shown in Fig. 3(b).

C. Correspondence Between Heaviness of Color and Color of Photoelasticity

It was observed that the perception of lightness and heaviness of color followed a clockwise pattern, starting with yellow in the hue circle. Therefore, as shown in Fig. 4, it becomes

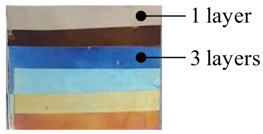


Fig. 5. Difference in coloration depending on the layers.

imperative to clarify how external forces induce color changes in photoelasticity, as explained in Section II-A.

Furthermore, it is essential to establish a correlation between the sequence of the color change and the progression of human perception regarding lightness and heaviness of color. In Section III, we investigate the establishment of a linear relationship between force and color for materials with photoelasticity. In Section IV, we investigate the structure that aligns with the human perception of lightness and heaviness, considering color variations induced by photoelasticity.

III. Relationship Between Color Change of Photoelasticity and Force

A. Materials and Color Change

To achieve the goal of this study, a soft, transparent material with photoelasticity that changes color in five different ways was required, as shown in Fig. 3(a). Because the purpose of this study does not include the discovery of materials that cause photoelasticity, we examined three commonly available materials: polyvinyl chloride (PVC) sheets, polyolefin films with a three-layer structure of polyethylene (PE), ethylene vinyl acetate (EVA), and polyethylene and thermoplastic polyurethane films. PVC sheets are difficult to process because they emit toxic gases when burned and cannot be laser cut. Thermoplastic polyurethane film has the flexibility of rubber but is brittle and easily torn via cuts resulting from processing. Therefore, we selected polyolefin film for this study. This material can facilitate the creation of diverse shapes, rendering it suitable for mass production. Fig. 5 shows the color generated by layering multiple sheets of a 0.3-mm-thick polyolefin film and sandwiching them between polarizing plates. The initial color saturation was greater when three or more layers of polyolefin films were stacked.

B. Shape and Color Change

For humans to visually comprehend the weight (force) indicated by color, the color corresponding to each force should be easy to identify. For example, as shown in Fig. 2(b), when force is applied, red and yellow become evident alongside blue, rendering it challenging to establish a clear relationship between force and color. Therefore, we consider a dumbbell shape as an example of a shape that can eliminate color irregularities by spreading the area of one color more widely. Based on Section VI.1.2 of JIS K7127 the shape is used to prevent stress concentration in the pulling tests and breaks in the gripping area. Fig. 6 shows the color change in photoelasticity in response to the strain (ε) of the dumbbell shape. In each case, a single color

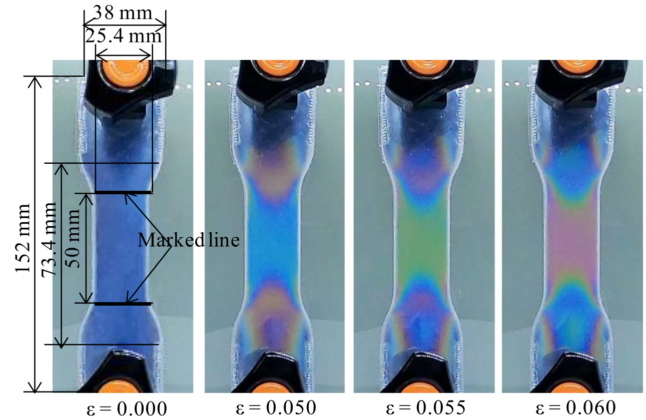


Fig. 6. Color change in response to strain.

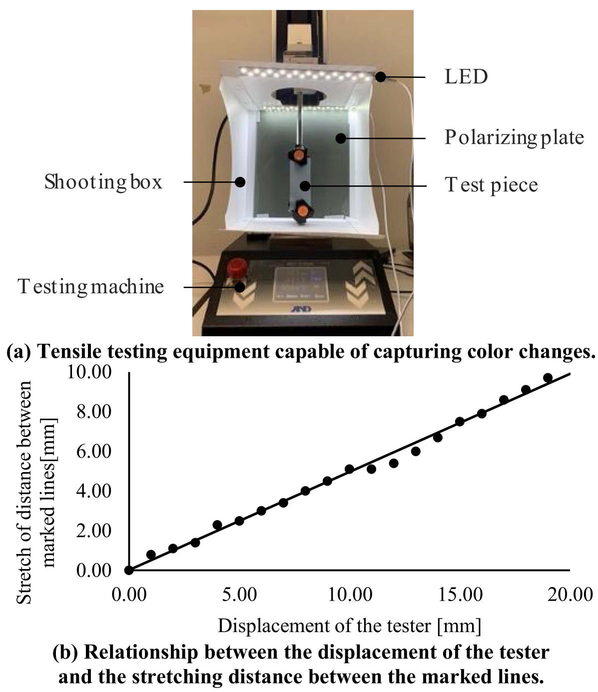
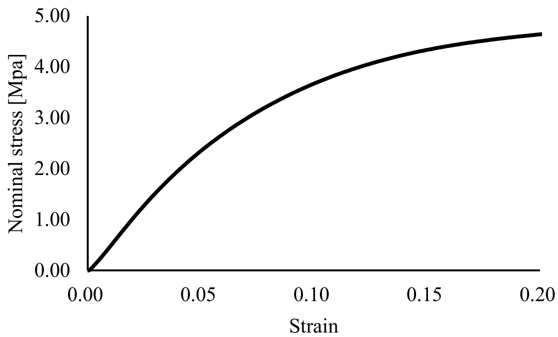


Fig. 7. Tensile test preparation.

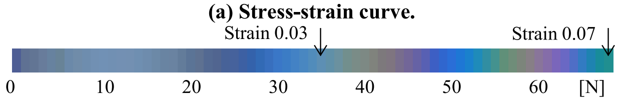
occupied the majority of the total area, making the colors easy to distinguish.

C. External Force and Color Change of Dumbbell-Shaped Material

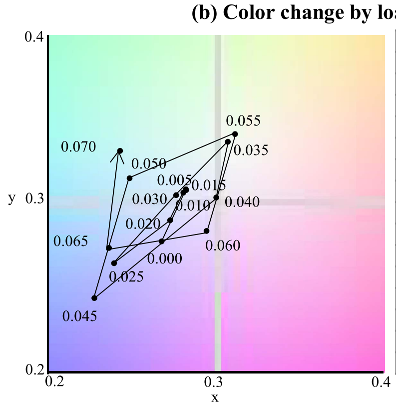
To determine the correlation between the external force and the color change in a dumbbell-shaped material caused by photoelasticity, the elastic region (where the relationship between the external force and stretch remains linear) was identified, along with the color change within that region. We conducted tensile tests on dumbbell-shaped test specimens made of three layers of 0.3 mm-thick polyolefin films. As shown in Fig. 7(a), a tabletop tensile and compression tester (A&D Corporation, MCT-2150W, minimum measurement resolution 0.01 N) was equipped with a shooting box to perform tensile tests while simultaneously recording videos of the color change of the



(a) Stress-strain curve.



(b) Color change by load.



Strain	R	G	B
0.000	78	94	149
0.005	103	130	159
0.010	113	144	179
0.015	105	132	162
0.020	81	101	144
0.025	56	111	190
0.030	104	141	177
0.035	125	137	132
0.040	120	109	141
0.045	48	102	206
0.050	49	142	162
0.055	124	133	123
0.060	133	109	169
0.065	50	123	194
0.070	32	143	144

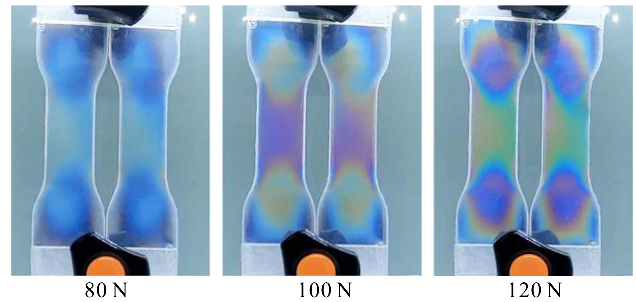
(c) Color change in response to strain.

Fig. 8. Results for a single connection.

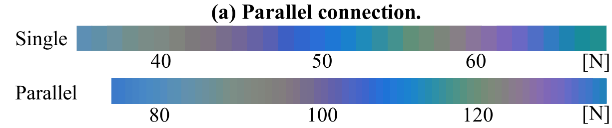
dumbbell-shaped test specimens at 60 fps. Polarizing plates were attached to the back of the shooting box and the front of the camera. The experiment was conducted in a windowless room with no natural light, and an LED light with a color temperature of 6500 K was lit inside the shooting box to standardize the color measurement conditions. The tensile tests were conducted at a displacement rate of 50 mm/min. In the tensile test, the entire dumbbell-shaped test specimen was stretched, but only the distance between the marked lines, where the color changed clearly, was subjected to the color change test. Therefore, based on the displacement of the tester, it is important to check the stretch of the distance between the marked lines. The stretch y [mm] of the distance between the marked lines relative to the displacement x [mm] of the tester is shown in Fig. 7(b). From this relationship, the relationship between x and y can be approximated:

$$y = 1/2x. \tag{1}$$

Fig. 8(a) shows the experimental stress-strain curves limited by the distance between the marked lines. The range of strain up to 0.07 and nominal stress up to 3.00 MPa is in the elastic region, and linearity is observed. Fig. 8(b) shows the color of the distance between the marked lines for each 1 N load. Blue continues to appear up to a strain of 0.03; however, after that, until a strain of 0.07, when the force and displacement are in the linear range, the color change due to photoelasticity is equal to two counterclockwise rotations of the hue circle in Fig. 3(b),



(a) Parallel connection.



(b) Comparison between single and parallel systems.

Fig. 9. Results of a parallel arrangement.

starting from blue. Furthermore, by converting the sRGB color space of the international standard defined by the International Electrotechnical Commission (IEC) into the CIE 1931 XYZ color space, the xy values corresponding to the RGB values for a strain of 0.005 were plotted and connected by lines as shown in Fig. 8(c). Because the range in which colors appear is limited, both the x and y values are plotted in the range of 0.2 to 0.4. As the strain increases, the color is seen to be generated in a clockwise spiral shape from the center. The RGB values were converted to XYZ and xy values as follows [13]:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$
$$x = X/(X+Y+Z)$$
$$y = Y/(X+Y+Z) \tag{2}$$

D. Handling of Various Loads

The forces exerted by machines and robots, as well as the loads they manipulate, vary depending on their intended purpose. Consequently, it is necessary to generate a color change in the photoelasticity proposed in this study, even for various load ranges. Therefore, we investigated the possibility of manipulating the appearance of optional colors at optional loads by altering the arrangement of dumbbell shapes as a single unit, as shown in Section III-B. We arranged two of the dumbbell-shaped test specimens shown in Fig. 6 in parallel and two in series, with the distance between the marked lines halved to 25 mm (referred to as Half-type). Parallel and series arrangements were tested in the same manner as described in Section III-C. The distance between the lines in the series arrangement is halved because of the height limit of the experimental equipment. Therefore, the experiment for a single test specimen of Half-type was conducted under the conditions described in Section III-C.

Fig. 9(a) shows the experiment using a parallel arrangement. Within the elastic region, known for its linearity, the color change observed in the parallel arrangement was compared to that observed in the single arrangement, as shown in Fig. 6.

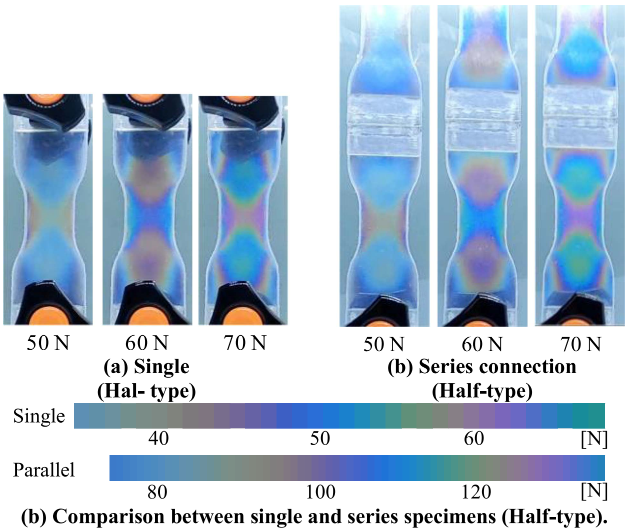


Fig. 10. Results for series arrangement.

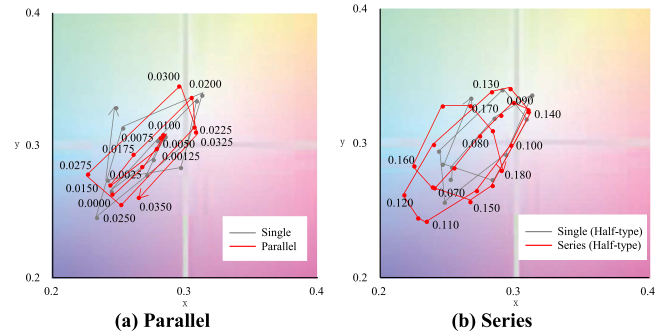


Fig. 11. Color and strain mapping for parallel and series arrangements.

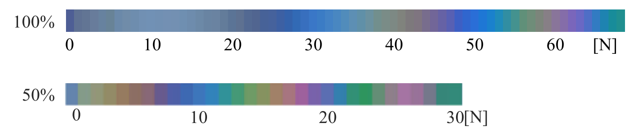


Fig. 12. Results for shrinking shape.

The results of these experiments are presented in Fig. 9(b). The color change was truncated below 40 N and 80 N owing to the persistent blue coloration without hue change within that range, as shown in Fig. 8(b). When two test specimens are connected in parallel, the load that a single test specimen receives is halved, and we can see that almost the same color is generated for every twice the load as when a single test specimen is connected. The divergence in color, that is, the gap in the cycle of change, was assumed to be an error in the fabrication of the test specimens. If we want to change the color in response to a larger load, we can use optional multiples parallel to the base shape, generating the same color.

Fig. 10(b) shows the experiment with a series arrangement. The color change in the series arrangement was compared with that in the single arrangement, as shown in Fig. 10(a). The results of the experiments are shown in Fig. 10(c). The color change was truncated below 40 N owing to the persistent blue coloration without hue change within that range, as shown in Fig. 8(b). The same color appeared at the same load as a single test specimen. When the test specimens were connected in series, the color was independent of the number of specimens connected. For example, when using this method on a machine or robot that deforms significantly, it is possible to display selected colors at different forces by arranging optional multiples in series.

As shown in Fig. 11, these results were mapped for the relationship between color and strain, similar to Fig. 8(c). In the case of the parallel arrangement, the color was generated in a clockwise spiral from the center at half the strain compared to the single system. In the case of the series arrangement, colors were generated in a similar but slightly different spiral shape.

E. Color Handling by Shrinking Dumbbell Shape

In addition to Section III-D, the possibility of controlling the appearance of a selected color at a selected load was examined by shrinking the dumbbell-shaped test specimens, as shown in Fig. 6, while maintaining the same ratio. The dumbbell-shaped specimens were shrunk to 50%. These experiments were conducted as described in Section III-D. Fig. 12 shows these results. Compared to the result of the original 100% shape, the color change becomes more pronounced within a smaller load range as the original shape reduces in size. Therefore, the desired colors can be obtained by shrinking the original shape appropriately when a small difference in force is required.

Furthermore, similar to the results in Section III-B and III-C, the reduction in size of the test specimens yielded a color shift in the photoelasticity that aligned with the counterclockwise order of the hue circle, as shown in Fig. 3(b), as the load increased. The exception to this rule is the third appearance of blue.

IV. Development of a Structure That Matches the Human Perception of Lightness and Heaviness to Color

A. Reverse Color Change of Photoelasticity

In Section III, we examine the quantitative relationship between load and color in materials with photoelasticity. When a tensile force was applied, the color appeared in the counterclockwise order of the hue ring, starting from blue. By contrast, as shown in Fig. 3(b), humans perceive colors as heavy in a clockwise order, starting from yellow to red. Therefore, if the color change of photoelasticity by an external force can be caused in the clockwise order of the hue circle, it is possible to match the human perception of lightness and heaviness, color, and the actual load change.

Specifically, as shown in Fig. 13, another elastic element was added to reverse the displacement of the polyolefin film, which generated photoelasticity in response to external forces. In this mechanism, as the external force increases, the tensile force on the dumbbell-shaped polyolefin film at both ends decreases, and the displacement decreases. This makes it possible to retrace the color change of photoelasticity from a counterclockwise change to a clockwise change in the hue circle as the external force is increased. Thus, the device produces a color that matches the

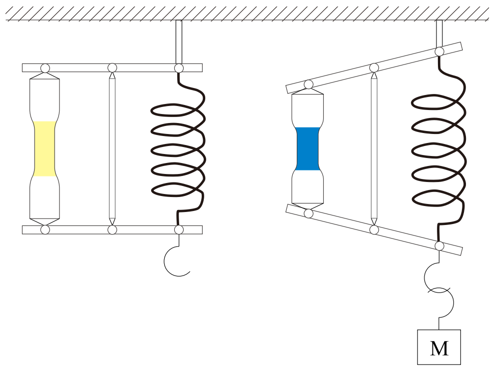


Fig. 13. Conceptual diagram of the reversal mechanism for color change using photoelasticity.

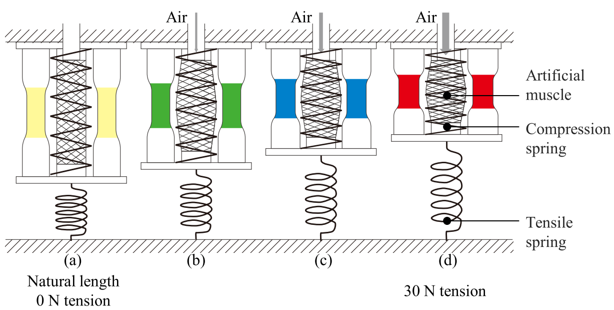
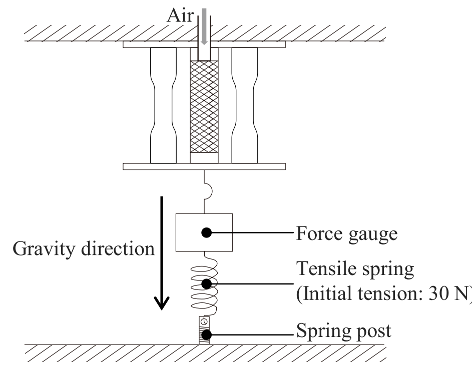


Fig. 14. Conceptual diagram of Ajisai mechanism.



(a) Conceptual diagram of the experimental equipment.

(b) Color of the 50% shape at a 15 N load.

Fig. 15. Actuation test.

human perception of lightness or heaviness in response to the external force applied to the device. In other words, as described in Section I, it is possible to construct a machine element, Ajisai that allows humans to understand force intuitively and visually from its color.

B. Combination With Actuators

Furthermore, we investigated a system that integrated a McKibben-type artificial muscle, exemplifying a soft actuator, to visually represent the force generated by active movement using color. The McKibben-type artificial muscle is a soft actuator powered by injecting a fluid, such as air, into a rubber tube covered with a mesh-like sleeve. The actuator generates a force through radial expansion when air pressure is applied. As shown in Fig. 14, the load change applied to the dumbbell-shaped polyolefin film, which changed the color of the photoelasticity, was reversed. When the actuator does not generate force, it is pulled by the compression spring, as shown in Fig. 14, such that the dumbbell shape becomes yellow, which is the lightest color shown in Fig. 3(b). Therefore, as shown in Fig. 14(a), the tensile spring representing the external force had a natural length, and the tension was 0 N. As pressure is applied, as shown in Fig. 14(b), (c), and (d), the actuator generates a larger force, the compression spring is compressed, the tension spring stretches to generate an external force, and the dumbbell shape's length is reduced. This causes a color change clockwise on the hue circle, transitioning from yellow to green, blue, and red.

C. Actuation Test

To assess the relationship between the force exerted by the actuator and the resulting color display, we conducted an experiment using the Ajisai system shown in Fig. 14 in Section IV-B. Fig. 15(a) shows a conceptual diagram of the experimental equipment. The system in Fig. 14 uses compression and tension springs; however, in the experiment, the tensile spring in Fig. 15(a) was tensioned from the beginning. The relationship between the force generated by the Ajisai system and the color can be verified by measuring the difference in the force generated after applying pressure to the artificial muscle using a force gauge (NEXTECH, HJ-DFS-X500, with a minimum measurement resolution of 0.01 kgf) and assessing the color of the resultant force. The dumbbell shape used is the 50% shape for which the relationship between force and color was clarified in Section III-E. The yellow color, which gives the lightest perception to humans, appeared when the loads were 3 and 15 N. In addition, in the direction of decreasing load, green, blue, and red appear only at 15 N. Furthermore, because this device has two dumbbell shapes connected in parallel across the artificial muscle, an initial tension of 30 N on the compression spring is required, as shown in Fig. 15(a). This indicates that, for this experiment, the tensile spring should be initially set with a downward tension of 30 N. The connected tensile spring, which had a spring constant of 2.16 N/mm, was equipped with a screw at the bottom to adjust the initial force. The screw was then rotated to adjust the initial force to 30 N. In the experiment, pressure was applied to the McKibben-type artificial muscle, and the values of the pressure gauge and force gauge were recorded when the color changed to green, blue, or red. As shown in Fig. 15(b), the separation between the marked lines in the 50% shrunken shape under a 15 N load is defined as yellow. Therefore, when the spring is stretched and the force gauge reading Is 30 N, the dumbbell shape should theoretically exhibit a yellow color, as shown in Fig. 15(b). However, owing to a manufacturing error, the observed color appeared greenish. Therefore, to align with the defined yellow color in Fig. 15(b), the spring post was rotated to adjust the color. This was used as the initial state in the experiment.

TABLE I
CORRESPONDENCE BETWEEN COLOR, PRESSURE, AND FORCE BY AIR SUPPLY

	Pressure gauge value after air supply [kPa]	Force gauge value [N]
Yellow	0	0.00
Green	152	1.08
Blue	171	1.76
Red	223	2.84

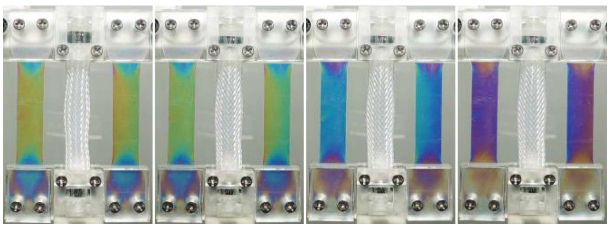
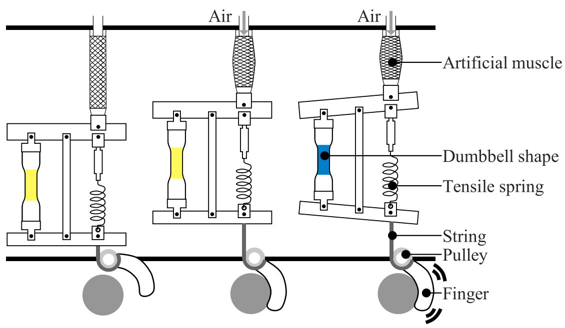
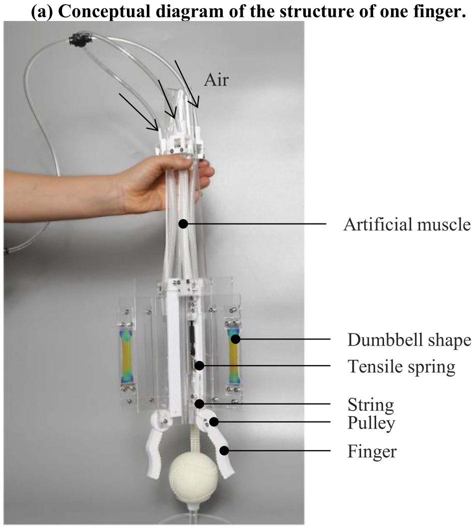


Fig. 16. Color change by applied force.



(a) Conceptual diagram of the structure of one finger.



(b) Three-fingered robotic hand.

Fig. 17. Robotic hand applied via Ajisai.

D. Experimental Results

Table I lists the experimental results, and Fig. 16 shows the Ajisai system and color change observed during the experiment. The units of the values measured using the force gauge were converted by equating 1 kgf to 9.8 N. The results indicate that as the output value of the Ajisai system increased, the color changed clockwise from yellow to green, blue, and red, following the order of the hue circle.

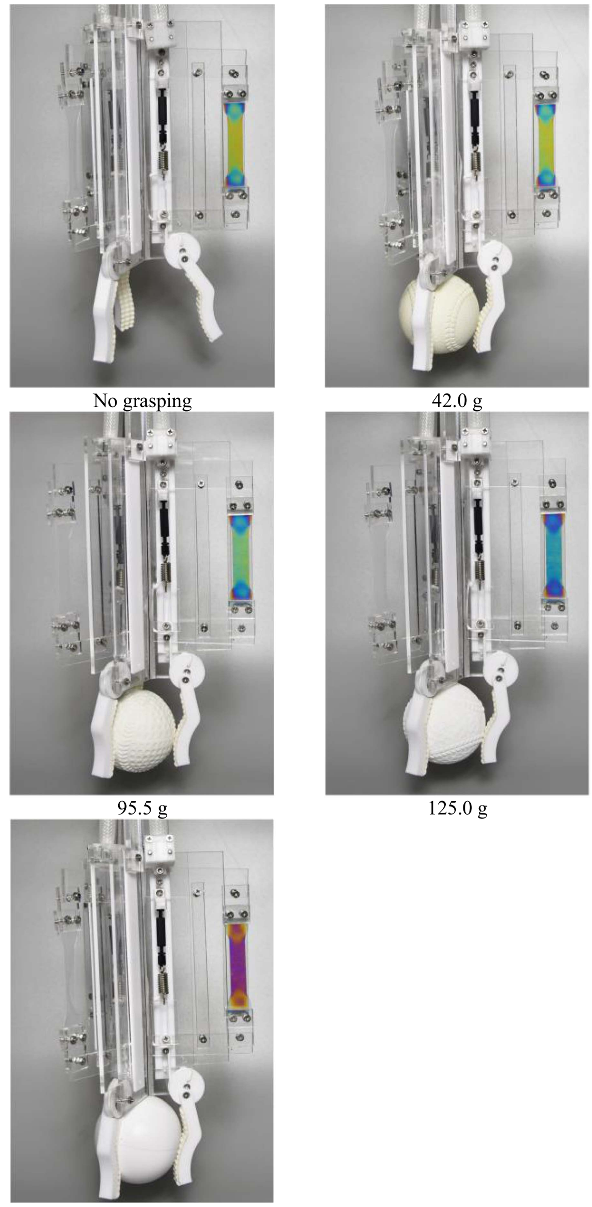
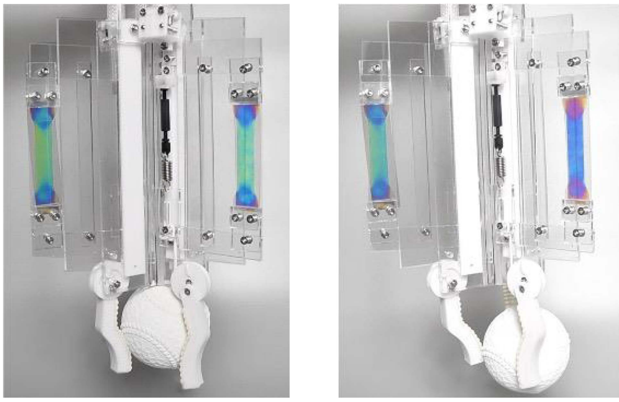


Fig. 18. Color change with the degree of exerted force.

IV. Development of a Robotic Hand Applied via Ajisai

A. Development of a Three-Fingered Robotic Hand

Using the Ajisai system developed in Section IV, we develop a robotic hand that can grasp an object. A conceptual diagram of the structure is shown in Fig. 17(a). The color of the hand changes according to the exerted force when the fingers grasp the object. The finger part closes by rotating the pulley when air pressure is applied to the artificial muscle. When there is no object, the lever only moves up and down in conjunction with the string. However, when resistance is applied to the fingers to grasp an object and the pulley does not rotate, the tensile



Stable Unstable

Fig. 19. Difference in grasping condition.

spring of the lever extends and the dumbbell shape compresses accordingly. By combining three structures at 120° intervals, the three-fingered robotic hand shown in Fig. 17(b) was developed.

B. Drive Tests and Experimental Results

We used three balls with diameters of 68 mm and weights of 42.0, 95.5, 120.0 and 250.0 g as grasping objects. The results are shown in Fig. 18. The three-fingered robotic hand with Ajisai gradually changed color from yellow to green to blue to red according to the object being investigated. Furthermore, the color difference between the fingers can indicate an unstable grasp, as shown in Fig. 19.

V. Conclusion

We have developed a mechanical element called Ajisai, which aims to convey visually the degree of force exerted by machines and robots on an object by aligning it with the human perception of the relationship between force and color. Humans perceive weight associated with the colors yellow, green, blue, and red, following the clockwise direction of the hue circle. Therefore, by developing a structure that changes color in this order, we can communicate force visually in a manner that corresponds to the human perception of the relationship between force and color.

To achieve this objective, we used the photoelasticity of a polymer material, which changes its color based on the internal force state. A tensile test was used to investigate the relationship between force and color using a dumbbell-shaped test specimen, which prevents stress concentration. During the test, we observed that the color appeared counterclockwise, starting from blue in the elastic region, where there is linearity between stress and strain. In addition, by using the dumbbell shape as a unit and using it in parallel, in series, or by shrinking the shape itself, it was found that selected colors could appear at selected forces.

To align with the human perception of color intensity and its association with lightness and heaviness, we induced a color change in the photoelastic material in the clockwise direction following the hue circle. The color change was synchronized with the actual increase in load. The developed system combines McKibben-type artificial muscles as soft actuators, and the dumbbell shape changes allow color changes from yellow to green to blue to red as the applied pressure or force increases. By applying the Ajisai structure, we developed a three-fingered robotic hand that changes its appearance color corresponding to the object.

In the future, Ajisai will be used as a component of a robotic arm in an environment where humans and robots work together.

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