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RESEARCH ARTICLE

Scalable and Foldable Origami-Inspired Supernumerary Robotic Limbs for Daily Tasks

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ABSTRACT This paper proposes scalable and foldable origami-inspired supernumerary robotic limbs that incorporate a continuous robotic mechanism to support activities of daily living and presents an analysis of the fabrication process, evaluation experiments, and potential applications of the proposed devices. These origami-inspired supernumerary robotic limbs can augment the wearer's capabilities by adjusting the scale of the devices to various applications and attaching them to parts of the body, such as the hands, wrists, arms, and torso. The device's foldable structure can be unfolded for use and folded when not in use to prevent physical contact with the wearer and the surrounding environment so that the user's movements are not restricted. In addition, the robotic limb is made of lightweight and soft material, so it remains safe to use and fatigue-free even after prolonged use. To verify the durability of the origami module, we conducted an experiment in which the module underwent 1,000 compressions using different materials and layer counts based on the folding pattern outlined in the manufacturing diagram. The experimental results showed that polypropylene was a suitable material for reducing fatigue due to folding, compared to polypropylene synthetic paper or plain paper. We also observed decreased stiffness with an increase in the number of layers. We believe that the proposed origami-inspired supernumerary robotic limbs can enlighten novel approaches to combining soft robotic and wearable devices.

INDEX TERMS Human augmentation, supernumerary robotic limbs, origami-inspired robot.

I. INTRODUCTION

Robotic and wearable devices play an important role in augmenting human capabilities. In the research field, the augmentation of physical abilities through wearable devices has been extensively explored. Such augmentation approaches can be categorized as follows: enhancing human capabilities with an exoskeleton [24], [41], wearing a prosthetic hand or leg [6], [18], and pushing the limits of human-capable tasks by attaching additional limbs [26], [38]. A number of wearable devices that extend human capabilities by attaching additional limbs have been studied with a focus on reducing the workload of industrial workers [5], [37] and supporting daily tasks [1], [36]. These devices are relatively smaller and lighter than conventional industrial robotic arms. However, they remain large and heavy for wearable devices. The small space between such a device and the human body may increase the risk of physical contact with the surrounding environment and the wearer. In this work, we propose a lightweight and compact design of robotic limbs that support daily tasks.

To resolve these issues, it is preferable that supernumerary robotic limbs (SRLs) can be attached safely to the human body in a folded position and deployed as needed [8], [36]. A comfortable and user-friendly experience for the wearer of the SRL is the key factor to be considered in the mechanism's

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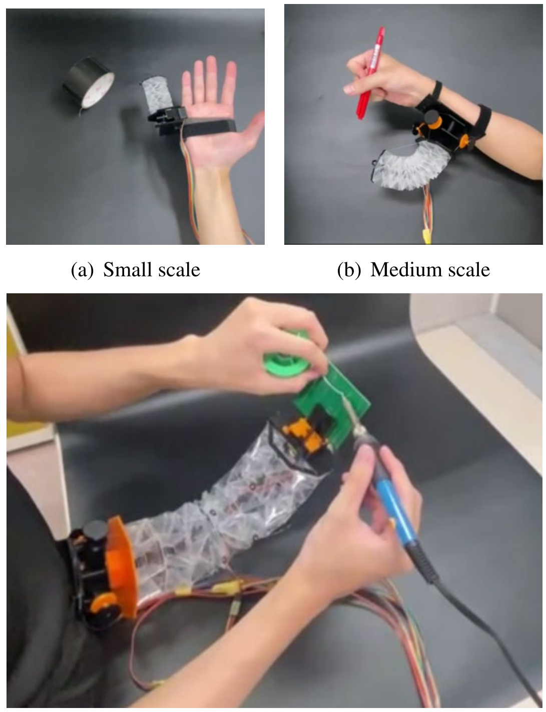
design. In addition, the scale of SRLs varies with their applications, from a sixth finger (small scale) to a third arm (large scale). A small-scale SRL (similar in size to a human finger) may encounter difficulties in naturally performing the tasks required by large-scale environments. Meanwhile, a large-scale SRL would represent an over-specification that is hard to control for tasks on the scale of finger motions. We believe that the scalability of the device design for diverse scales and applications is crucial in different contexts and usage situations. A further challenge is to provide non-skilled users with the accessibility and flexibility necessary to fabricate an SRL of a suitable scale for their own purposes with available interfaces and materials.

Origami is a traditional hobby enjoyed by a wide range of age groups. It involves making various structures from a single sheet of paper. On the other hand, the geometric properties and flexibility of origami structures have been gaining increasing attention in modern design and engineering [19]. With the evolution of digital fabrication and computational techniques, the design of robotic mechanisms inspired by origami has emerged as a novel approach to address the limitations of traditional rigid structures. Origami-inspired structures are widely applied in various fields, ranging from large objects such as satellites to very small electronic devices. First, the use of origami structures allows for lightweight design [28], which makes products and structures easy to transport and handle. Second, origami-inspired structures are highly scalable, meaning that their flexible design and manufacturing processes allow for their adaptation to various sizes and applications. In addition, origami structures are suitable for rapid manufacturing processes due to their relatively simple structures and assembly procedures, in contrast to traditional manufacturing processes [20]. Furthermore, origami structures provide both flexibility and stability which allow them to deploy flexibly when needed and to fold compactly when not in use [10]. This maximizes space efficiency. Given these advantages, this study aims to apply origami-inspired structures to solve the above challenges of SRLs simultaneously.

In this work, we propose scalable and foldable origami-inspired SRLs as shown in Fig. 1, especially the twisted tower origami structure, which is adopted in robotic mechanisms for its superior bending and stiffness performance. First, we verified origami-inspired structures suitable for the intended application and proposed a fabrication method using a laser cutter. In performance evaluation experiments, we investigated durability by varying materials and layer numbers. The results showed that polypropylene exhibited the highest durability, and it became evident that stiffness decreases with an increase in the number of layers. Finally, we verified the effectiveness of applications in daily tasks in different scenarios.

The main contributions of this work are listed as follows:

- We propose a fabrication technique of origami-inspired SRLs using a twisted tower structure with adjustable layers and scale.
- We verify the proposed SRLs for durability using different materials.
- We design SRLs that combine scalability and foldability in different use scenarios.



(a) Small scale (b) Medium scale

(c) Large scale

FIGURE 1. Prototypes of scalable and foldable origami-inspired supernumerary robotic limbs at different scales in this work.

II. RELATED WORKS

A. SUPERNUMERARY ROBOTIC LIMBS

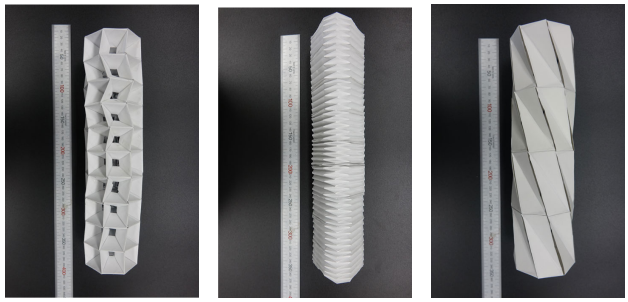
SRLs are wearable robotic devices designed to enhance human capabilities, assisting with tasks that were previously impossible due to physical limitations or making them more efficiently achievable. Normally, SRLs are thought of as extensions of the human body that operate as part of the body [2], enabling actions beyond the limitations of the physical body. While exoskeletons are also parts of the human body that are inherently present through robotic devices, SRLs enhance humans by endowing them with independent devices. SRLs can improve the quality of life for people with physical disabilities and promote the broader enhancement of human capabilities. Recently, SRLs research has been actively conducted with various applications that mimic fingers, arms, and legs. Small-scale SRLs function primarily as fingers and have been used to improve the user's grasping ability [25] and to assist in piano playing [7]. Cable-driven soft robotic fingers have also been developed [11]. Medium-scale SRLs are mainly attached to the forearm [32] and assist people with hand disabilities [33], soft robotic fingers for stroke patients [12], and two robotic fingers [17]. Other SRLs utilize programmable joints to perform various tasks [16], while others are pneumatically driven to assist in grasping [30]. Large-scale SRLs are often used for industrial applications [4], [22], [23]. They can handle different tasks with different scale sizes. In this work, we aim to design scalable SRLs covering different scales, thereby expanding the range of tasks that can be handled.

B. ORIGAMI-INSPIRED ROBOTICS

Origami structures, such as the twisted tower structure, the Yoshimura pattern, and the Kresling pattern, are usually adopted in the construction of robotic arms due to their respective mechanisms [14]. The twisted tower structure is a multi-layered origami structure capable of linear extension and bending with twisting. Some studies of soft robotic arms using the twisted tower structure have proposed fabrication methods using 3D printers and others have been fabricated using only rigid parts [35]. In addition, there is a robotic arm that is operated by a cable-driven in the twisted tower structure [31]. Moreover, the twisted tower structure has applications not only as a robotic arm but also as a mobile robot [9]. The Yoshimura pattern is a familiar cylindrical origami structure with the property of contracting when an external force is exerted axially on the thin cylinder. Yoshimura patterns usually have a consistent diamond lattice structure. With regard to structural properties, Yoshimura pattern structures have high torsional stiffness and deformability. In the study of robotic arms using the Yoshimura pattern, a flexible manipulator was developed by proposing a modular robotic arm [27]. Other studies include the development of a mobile robot using the Yoshimura pattern [21] and a robot capable of spontaneous locomotion [3]. An origami structure with a Kresling pattern can cause axial contraction and extension by twisting the upper and lower surfaces of cylindrical bodies. This structure consists of a set of triangles with the same geometrical parameters. The upper and lower surfaces of the cylindrical body are usually regularly shaped polygons. This structure has bistable characteristics and two stable states: extended and contracted. Each state has unique mechanical properties [34]. A robotic arm that can be reconfigured to take advantage of these features has been constructed [13]. The degree of freedom of the robotic arm can be modified by selecting links and joints.

III. ORIGAMI-INSPIRED SUPERNUMERARY ROBOTIC LIMBS

In this work, we adopt origami-inspired supernumerary robotic limbs to propose scalable and foldable mechanisms. Common robotic arms inspired by origami structures usually adopt the twisted tower, Yoshimura pattern, and Kresling pattern. For each of these patterns, we conducted a preliminary study to analyze its characteristics in folding process and mechanic performance(Fig. 2). In our preliminary study [14], all three origami structures exhibited low out-of-plane stiffness, but the Yoshimura pattern performed particularly poorly in this regard. When tilted parallel to the ground, it was unable



(a) Twisted tower (b) Yoshimura pattern (c) Kresling pattern

FIGURE 2. Three structures of origami-inspired robotic arms.

TABLE 1. Comparison results of three types of origami-inspired robotic mechanisms (TT: twisted tower, YP: Yoshimura pattern, KP: Kresling pattern).

Origami structures	TT	YP	KP
Stretch Performance Ratio	6.7	9.7	15.0
Bending Performance [°]	130	205	53
Production Time [h]	12.0	4.5	2.5
Out-of-plane Stiffness	✓	×	✓

to bear its own weight and drooped, revealing limitations in the tasks it can handle. The Kresling pattern is not scalable because it is difficult to adjust the number of layers in the development diagram. The comparison results of the three types of origami-inspired robotic mechanisms are shown in Table 1. We used four aspects to evaluate the three structures: stretch performance, bending performance, production time, and out-of-plane stiffness. Stretch performance refers to the ratio of the natural length to the length when contracted. Bending performance represents the angle between the upper and bottom surfaces when bending occurs. Out-of-plane stiffness is considered with the cylinder direction as the axis. According to our manually fabricated results (Fig. 2), all structures achieved good stretch performance values (TT = 6.7, YP = 9.7, KP = 15.0). For bending performance, the Kresling pattern had the worst mean scores for bending angles (TT = 130°, YP = 205°,, KP = 53°). In terms of production time, the twisted tower had the most time-consuming folding process (TT = 12, YP = 4.5, KP = 2.5 hours). In view of these performance results, we adopted the twisted tower structure for scalable and foldable SRLs in this study.

A. KINEMATICS OF TWISTED TOWER

We analyzed the kinematics of twisted tower structure as a rigid body in this study. The top and bottom surfaces of twisted tower are regular octagons. If the length of one layer of the octagon is a, the radius of the circumscribed circle of the octagon is r, the number of layers is n, and the height is h, the radius r of the twisted tower structure (Fig. 3) can be calculated as follows:

$$r = \frac{a}{2\sin(\frac{\pi}{8})} \tag{1}$$

$$h = a * n \tag{2}$$

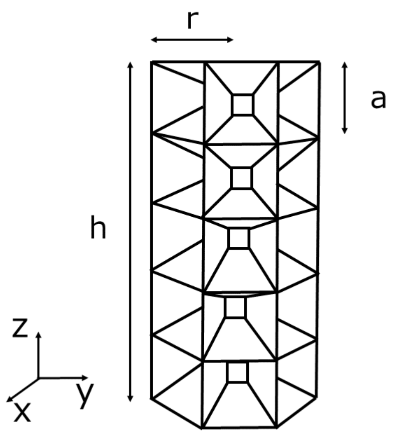


FIGURE 3. Illustration of twisted tower structure.

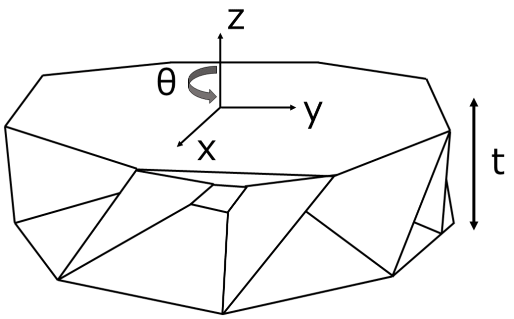


FIGURE 4. Linear motion of twisted tower structure.

The number of faces of a regular octagon is expressed as $n+1$, and if the torsion angle of adjacent faces is θ, the torsion range is expressed as follows:

$$-\frac{\pi}{4}+\varepsilon_t \leq \theta \leq \frac{\pi}{4}-\varepsilon_t \tag{3}$$

Here, ε_t represents the angle between the top and bottom surfaces after a complete rotation due to the thickness of the material. If pure torsional motion is generated on adjacent surfaces, the surfaces remain parallel, and a linear displacement t (Fig. 4) in the distance between the surfaces occurs as in the following equation:

$$t=-\frac{4a}{\pi}|\theta|+a \tag{4}$$

If no torsion occurs (θ=0), no axial displacement occurs, and the distance is a. If the torsion approaches its maximum ($\theta= -\pi/4, \pi/4$), the distance becomes smaller. In addition, the displacement at layer n (Fig. 5) is calculated as follows:

$$t_n=-\frac{4a}{\pi}\sum_{i=1}^{n}|\theta_i|+an \tag{5}$$

The rigid body transformation is expressed as follows:

$$T_{linear}=Trans(0,0,t_n)Rot(z,\theta) \tag{6}$$

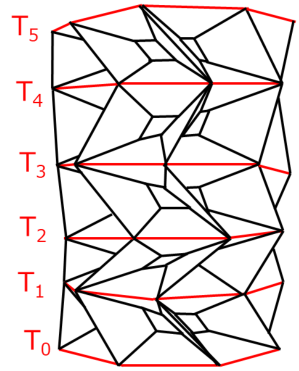


FIGURE 5. Total linear motion of 5-layer twisted tower as an example.

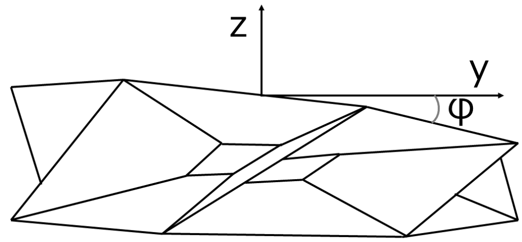


FIGURE 6. Bending motion of one layer structure.

In the case of layer n, it is as follows:

$$T_{n_{linear}}=\begin{bmatrix}\alpha & -\beta & 0 & 0\\ \beta & \alpha & 0 & 0\\ 0 & 0 & 1 & t_n\\ 0 & 0 & 0 & 1\end{bmatrix}$$

where $\alpha=\cos\left(\sum_{i=1}^{n}\theta_i\right)$, $\beta=\sin\left(\sum_{i=1}^{n}\theta_i\right)$, respectively.

When a bending motion occurs (Fig. 6), the bending angle can be represented as ϕ, and the displacements of y and z generated by the bending motion are denoted as y' and z', respectively, yielding the follows:

$$T_{bending}=Trans(0,y',z')Rot(z,\theta)Rot(x,\phi) \tag{7}$$

In the case of layer n (Fig. 7), it is as follows (the displacements in layer i are denoted as y'_i and z'_i, respectively):

$$T_{n_{bending}}=\begin{bmatrix}\alpha & -\beta & 0 & 0\\ \beta\gamma & \alpha\beta & -\delta & \epsilon\\ \beta\delta & \gamma\delta & \gamma & \varepsilon\\ 0 & 0 & 0 & 1\end{bmatrix}$$

where $\gamma=\cos\left(\sum_{i=1}^{n}\phi_i\right)$, $\delta=\sin\left(\sum_{i=1}^{n}\phi_i\right)$, $\epsilon=\sum_{i=1}^{n}y'_i$, $\varepsilon=\sum_{i=1}^{n}z'_i$, respectively.

IV. FABRICATION PROCESS

Our proposed fabrication method is based on the development of a twisted tower [29] and uses laser cutting. This avoids the burdensome traditional method [9], and allows for a scalable

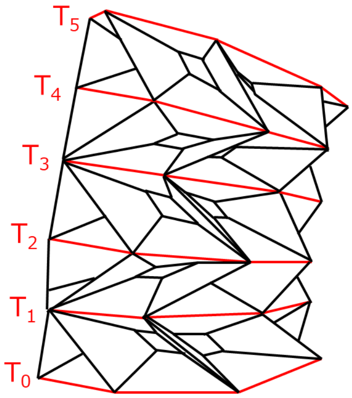


FIGURE 7. **Total bending motion of 5-layer twisted tower as an example.**

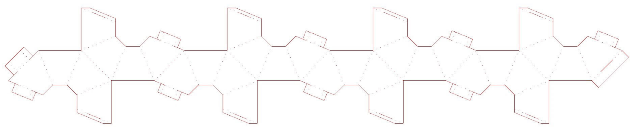
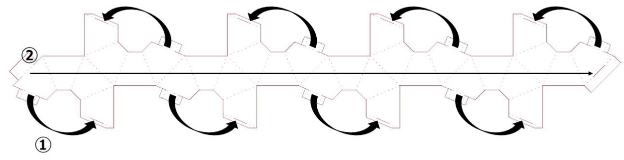
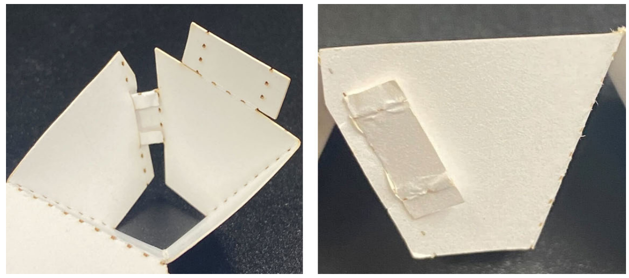


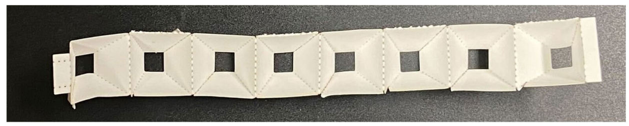
FIGURE 8. **Diagram of twisted tower.**



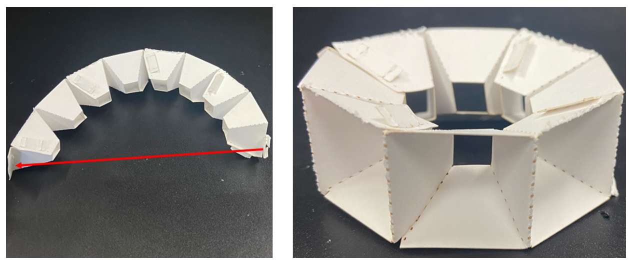
(a) Folding from step 1 to step 2.



(b) Inserting two end-parts (left) and spreading it out (right).



(c) The fabrication results after step 1 in (a).



(d) The left subfigure shows the fabrication result after step 2 in (a), and the right subfigure is the completed state.

FIGURE 9. **Folding process for assembling one layer of twisted tower structure.**

design. In the development diagram (Fig. 8), a trick was used to avoid the use of tape for fixing. This further reduces the amount of work for the user. The fold line area was made into a dotted line to assist the user in folding it; the folding procedure for one layer is shown in Figure 9. As shown in Figure 9(a), the user needs to insert the trick into the slit.1 This is done for eight locations. Once the outside of the trick is folded and inserted into the slit, it is opened to prevent it from falling out of the slit (Fig. 9(b)). The result of this process is shown in Fig. 9(c). Next, a one-layer twisted tower is completed by connecting the tricks and slits at both ends (Fig. 9(d)). The manufacturing process is shown in Fig. 10. The user first uses the interface implemented by Grasshopper. The user can customize the scale and number of layers of the twisted tower and a development diagram is created according to the parameters determined by the user. The created development diagram is saved in SVG format and imported into the software for use with the laser cutter. The sheets cut out as per the development diagram are folded by the user to complete the twisted tower module. The laser cutter used was the SP500 from Trotec Laser Japan Ltd.

V. PERFORMANCE EVALUATION

The spring-like properties of the twisted tower are crucial. At the same time, origami possesses the limitation of not regaining its original form following extended usage due to fatigue. Therefore, the durability of the twisted tower structure was assessed by altering the materials and number of layers. The origami structure was compressed in the axial direction and returned to its original shape 1,000 times. This permitted the determination of the stiffness and durability of the origami during extension and contraction movements. The material's thickness remained at 0.25 mm while the spacing of the dotted lines on the folds was consistently maintained. As in the diagram, each layer had a height of 24.5 mm and a displacement of 20 mm per layer. The ZTA-50N load-measuring instrument, manufactured by IMADA Co., was utilized in the experiment (Fig. 11). Experimental procedures 1) to 6) are described as follows.

1) Move the plate until it touches the upper surface of the origami samples.
2) When touching the surface, the plate is kept moving downward with a small amount of displacement in such a way that the Force Gauge displays a negative force value (approx. -1N to -2N) to make sure the plate contacts the origami samples.
3) Subsequently, the force value is set to 0 N, ensuring that the force value will be 0 N at the starting point of the 1st cycle.
4) Determine the maximum displacement (mm) based on the desired displacement of each layer and the number of layers of origami designs.
5) Return the plate to the starting point, where the force value was set to 0 N beforehand.

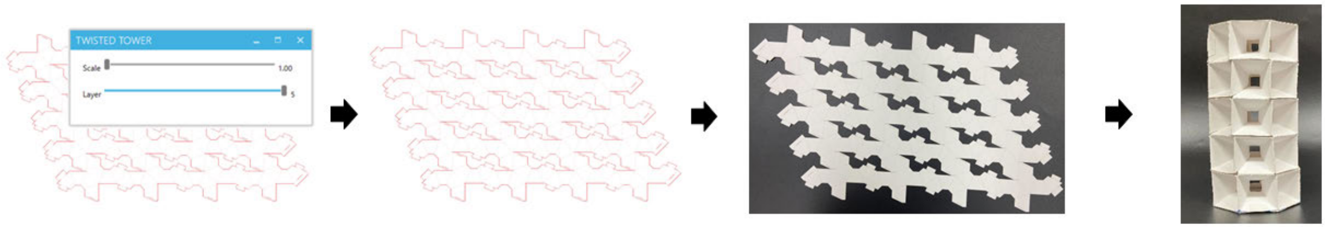


FIGURE 10. Fabrication process of twisted tower. First, the user can adjust the size and scale parameters through user interface. Next, the development is saved in SVG format according to the size and number of layers determined by the user. The development sheet created by the laser cutter is folded by hand by the user to complete the product.

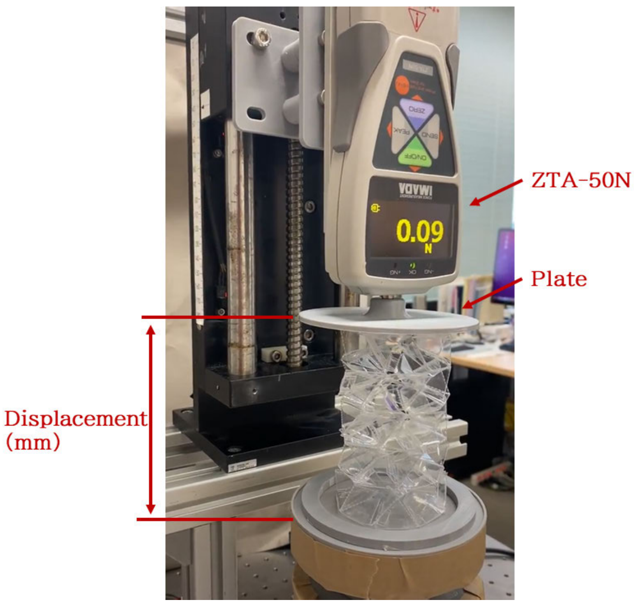


FIGURE 11. Experiment setup for performance evaluation.

6) Execute the MATLAB code to start the testing cycles (1,000 cycles).

A. MATERIAL TEST

Experiments were carried out with different materials to find the most suitable. In this experiment, the origami structure was compressed in the axial direction and then returned to its original position for three different materials to clarify the differences in performance due to the different materials. All the materials were combined in a five-layer structure. The estimated height obtained from the development diagram is 122.5 mm, but there is an error depending on the material. The materials used were inexpensive and readily available polypropylene (Johoku pp-sheet 0.25mm), polypropylene synthetic paper (Paper Entrance Yupo FGS 0.25mm), and paper (Fujisan Kikaku Kogyo 0.25mm). The results are shown in the Fig. 12. The vertical axis is the load [N], and the horizontal axis is strain [%]. The initial cycles (starting at 0) are represented by the blue lines, and the later cycles (up to 1,000) by the red lines. When the origami structure is at its maximum displacement, it exhibits the highest stiffness.

TABLE 2. Stiffness comparison with different layers.

Number of layers	3	5	7
Stiffness between two points (N/mm)	0.148	0.071	0.048

Fatigue was observed after several cycles in all three samples, and similar curves were obtained for each. In the post-test samples, paper fatigued the most, followed by polypropylene synthetic paper (Fig. 13). Polypropylene showed little effect after 1,000 cycles of expansion and contraction. The large difference in the load at the maximum displacement for each of the materials is considered an error due to the manual folding of the origami paper. This indicates that polypropylene is the most suitable material.

B. LAYER CONSTRUCTION TEST

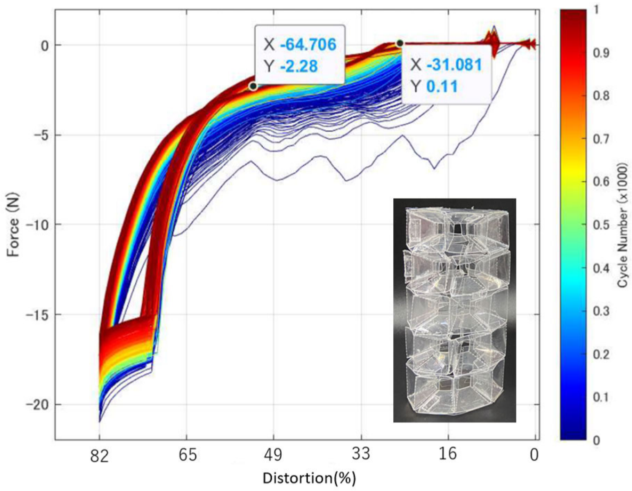
Next, experiments were conducted with different numbers of layers. The results are shown in Fig. 14. The estimated heights of the 3 and 7 layers are 73.5mm and 171.5mm, respectively. Similar curves were obtained. From the figure, two arbitrary points were selected from the linear region between 800 and 1,000 cycles to obtain the stiffness (Table 2). The results show that the stiffness decreases as the number of layers increases. This demonstrates similar properties to the twisted tower in conventional fabrication methods [9]. The large difference in load at maximum displacement in this experiment is considered to be an error due to hand folding.

VI. RESULTS AND DISCUSSION

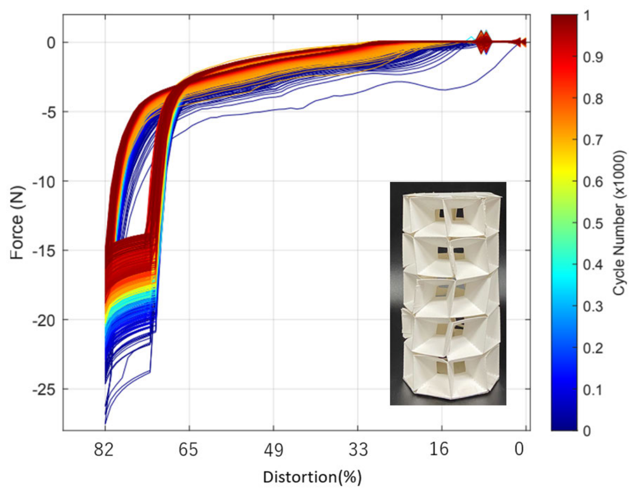
This section describes the details of the implementation of the proposed origami-inspired structure at different scales. For more details, please refer to the supplementary video.

A. IMPLEMENTATION DETAILS

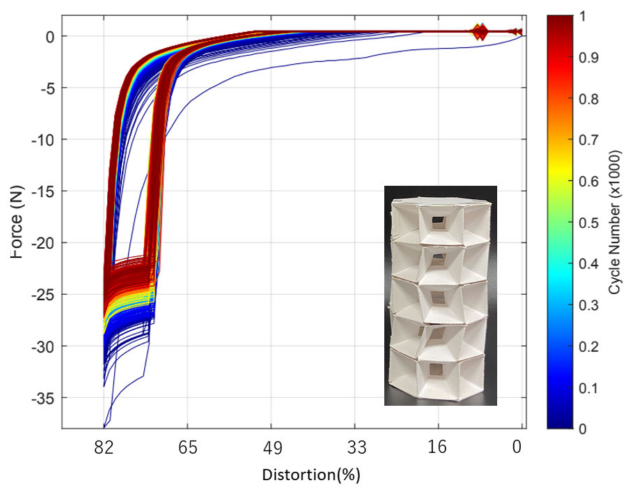
We aim to propose wearable devices using the fabrication approach of origami-inspired SRLs that can be attached to the user's hand, arm, or torso. Thus, three sizes of twist towers were fabricated (small, medium, and large scale), which were designed to correspond to specific tasks. While the small-scale SRLs are powered by two motors, the medium- and large-scale SRLs are driven by an actuation module with up to four motors (Fig. 15). The wire attached to the top surface of the twisted tower is connected to a motor



(a) Polypropylene



(b) Polypropylene synthetic paper



(c) Paper

FIGURE 12. Experimental results for a 1000 cycle fatigue test. Loads and strains are plotted for the materials: polypropylene (a), polypropylene synthetic paper (b), and paper (c).

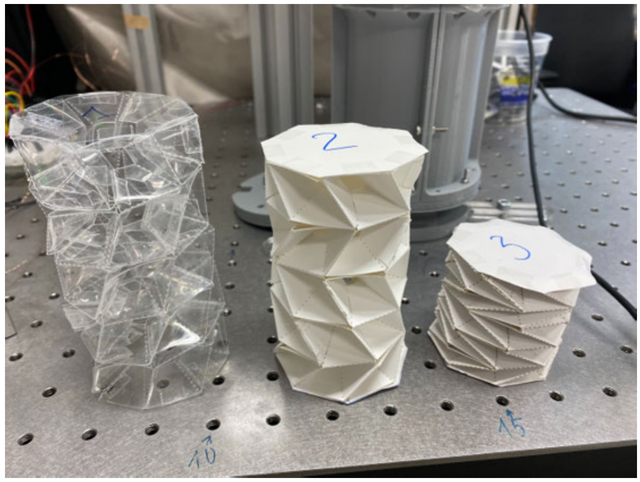


FIGURE 13. State of the three materials after the experiment. Polypropylene on the left, polypropylene synthetic paper in the center, and paper on the right.

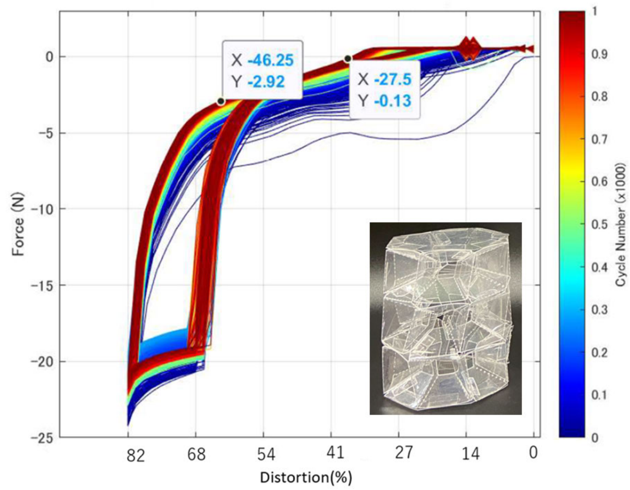
equipped with a rotary encoder (Magnetic Encoder Pair Kit for Pololu Micro Metal Gearmotors, 12 CPR) through a spool mechanism (Pololu 380:1 Micro Metal Gearmotor HP 6V with Extended Motor Shaft). The wire used is made of nylon with a diameter of 0.43mm. The microcontroller utilized is an Arduino Mega 2560, and the motor driver is TB6612FNG. The figure illustrates the operation of the twisted tower: when the motors are activated, the wire is retracted, causing the twisted tower to contract (Fig. 16 (b)). Conversely, reversing the direction of the motors allows the twisted tower to return to its extended state due to the spring-like characteristics of the structure. Additionally, by using a single motor, a bending motion can be achieved, and by controlling multiple motors appropriately, bending motions in any direction can be achieved (Fig. 16 (c)).

B. SIXTH FINGER AT SMALL SCALE

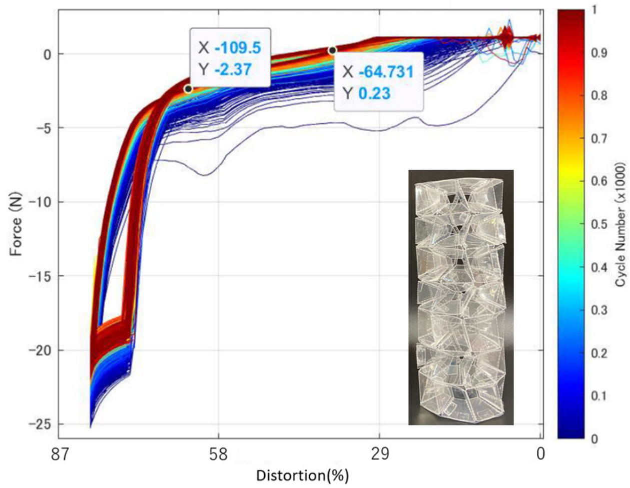
Small-scale twisted towers are compact and versatile in design. Our prototype design adopted a 6-layers twisted tower structure of radius $r = 19.5$ mm, the length of one layer $a = 15.0$ mm, height $h = 90.0$ mm, and weight of 7.0 g. Potential applications can be used in assisting in lifting objects (Fig. 17) or grasping large objects (Fig. 18). It can effortlessly maneuver and lift a variety of objects, contributing to increased efficiency and convenience in a variety of daily tasks. The system ensures safe and secure object handling and provides users with a reliable tool for their daily lifting needs. It is an indispensable aid that is easy to use, streamlines the object-handling process, and contributes to increased productivity.

C. THIRD FOREARM AT MEDIUM SCALE

For our prototype design at the medium scale, we adopted a 10-layers twisted tower structure of radius $r = 30.0$ mm,

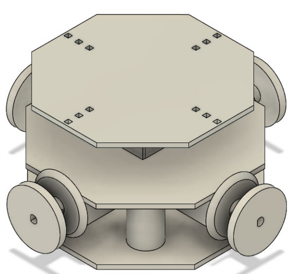


(a) 3 layers

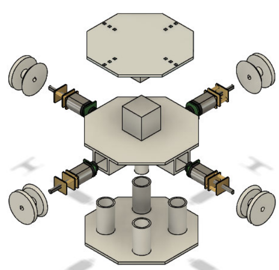


(b) 7 layers

FIGURE 14. **Experimental results with different layers made of polypropylene material: 3 layers (a) and 7 layers (b).**



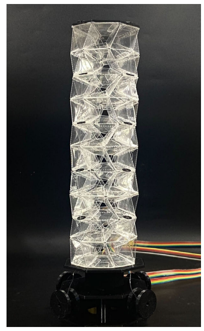
(a) Module for medium scale



(b) Constituent parts

FIGURE 15. **Actuation module and parts inside.**

the length of one layer $a = 23.0$ mm, height $h = 230.0$ mm, and weight of 26.0 g. The medium-scale twisted tower attached to the forearm is used to hand a pen to the user (Fig. 19); it allows lifting objects without using the hands (Fig. 20). It is initially folded but can be extended to perform its intended function. The arm parts can be bent to facilitate the task of passing a pen or holding an object. Once the task is completed, it is extended again before returning to its original folded state. This mechanism is designed to assist in the accurate performance of everyday tasks while allowing



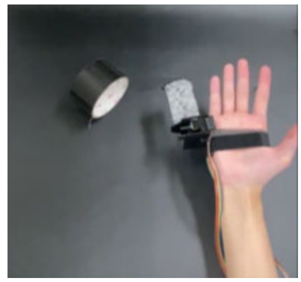
(a) Normal state

(b) Folding state

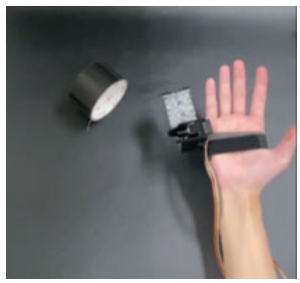
(c) Bending state

FIGURE 16. **Wire-driven actuation for the control of the SRLs with the twisted tower structure in normal (a), folding (b), and bending states (c).**

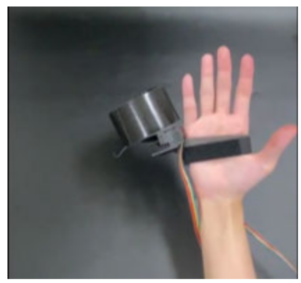
(a) Folding state



(b) Extended state



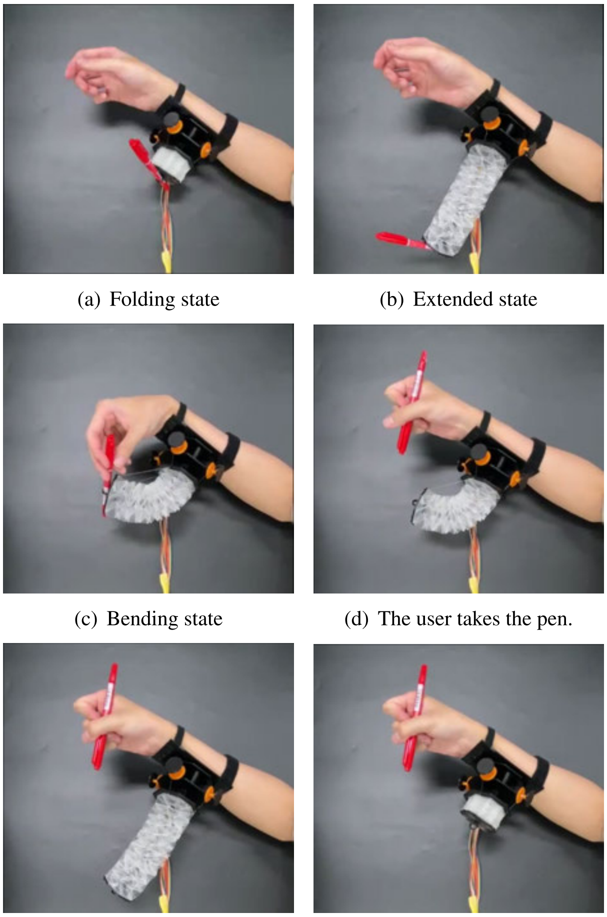
(c) Bending state



(d) The user lifts the object.

FIGURE 17. **Object hooking task (Max lifting force: 5.9[N]). A 6-layer small-scale twisted tower with a diameter of 39 mm and a height of 90 mm. The device is attached next to the little finger and used to hook the tape.**

FIGURE 18. **Large object grasping task (Max grasping force: 1.06[N]). A 12-layer small-sized twisted tower with a diameter of 39 mm and a height of 180 mm. The device is attached near the wrist and used to grasp a large object with one hand.**

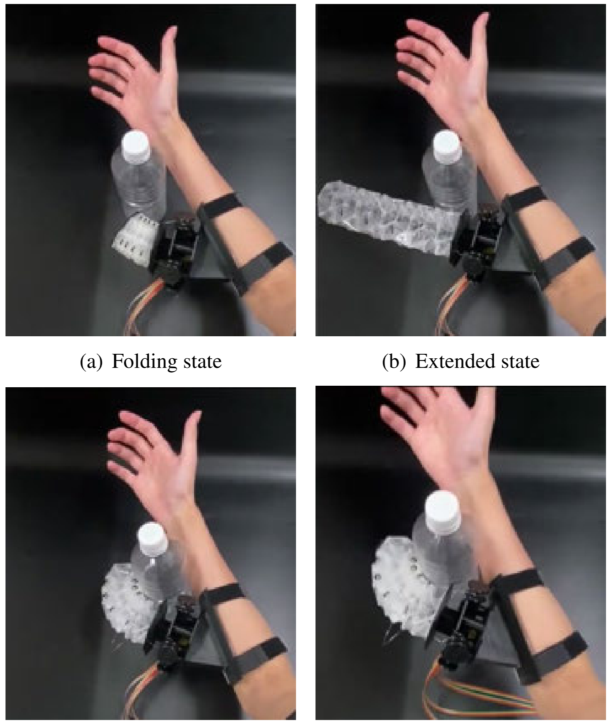


(a) Folding state (b) Extended state

(c) Bending state (d) The user takes the pen.

(e) Extended state (f) Folding state

FIGURE 19. Handover task (Max lifting force: 2.7[N]). A 10-layer medium-sized twisted tower with a diameter of 60 mm and a height of 230 mm. The device performs an extension and bending motion from the folded state to pass the pen to the user. After completing the task, the device returns to the folded state.



(a) Folding state (b) Extended state

(c) Bending state (d) The user lifts the object.

FIGURE 20. Object pinching and lifting task (Max grasping force: 1.06[N]). A 10-layer medium-sized twisted tower with a diameter of 60 mm and a height of 230 mm. The device performs an extension and bending motion from the folded state to lift an object without the use of hands.

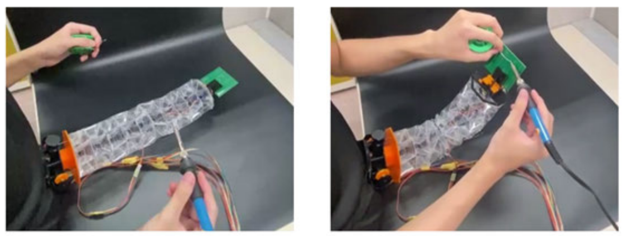


FIGURE 21. Soldering task. A 10-layer large-sized twisted tower with a diameter of 73 mm and a height of 280 mm. The device has a substrate at the end to support soldering tasks.

freedom of hand movement. It is particularly useful for people with restricted body movements or certain disabilities. The device is designed for ease of use and comfort, taking into account its range of applications and safety.

D. THIRD ARM AT LARGE SCALE

For our large-scale prototype design, we adopted a 10-layers twisted tower structure of radius $r = 36.5$ mm, the length of one layer $a = 28.0$ mm, height $h = 280.0$ mm, and weight of 36.0 g. The large-scale twisted tower is mounted on the fuselage to enhance the accuracy and efficiency of soldering operations (Fig. 21). The adjustable and agile mechanism allows access to hard-to-reach areas and is easy to operate. It is also comfortable and easy to use, minimizing fatigue and maximizing productivity during long soldering operations.

E. DEVICE PERFORMANCE EXPERIMENTS

To investigate the performance limits of the proposed devices, we measured the lifting and grasping forces for all sizes of the twisted tower modules at small, medium, and large scales.

1) LIFTING FORCE

We conducted experiments to measure the lifting forces of the proposed device. The experimental setup is shown in Fig. 22. The origami samples were fixed on a linear guide. A wire attached to the tip of the origami sample was connected to a 3-axis force sensor, USL06-H5-50N model, of the Tec Gihan brand. When the linear guide is actuated upward for a certain distance, the wire becomes taut, and a force is generated in the direction of F_L. The values obtained by the force sensor are processed via the amplifier DSA-03A and the force AD converter; subsequently, this force data was collected by their specialized software and exported to CSV-extension files.

From Table 3, we found that lifting force was 5.9[N] for the 6-layer small-scale device, 2.7[N] for the 10-layer

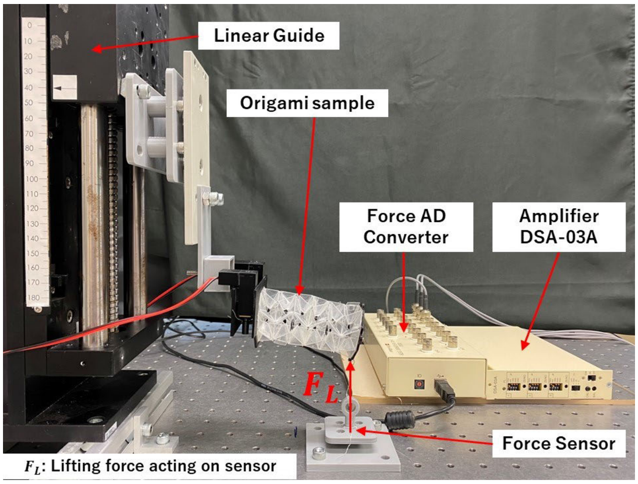
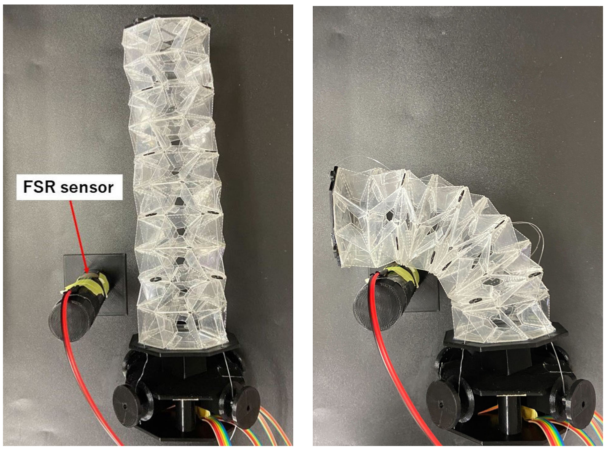


FIGURE 22. Experiment setup for measuring lifting force.



(a) Experiment setup (b) Contact with FSR sensor

FIGURE 23. Measurement of grasping force by FSR sensor.

medium-scale, and 2[N] for the 10-layer large-scale ones. We observed a decrease in the lifting force with an increase in the axial length of the proposed devices.

2) GRASPING FORCE

In this study, we used a Force Sensitive Resistor (FSR) sensor to measure grasping force, following the method of Lee et al. [15]. In the measurement, we bent the proposed device from the normal state and brought it into contact with the FSR sensor (Fig. 23). In addition, we conducted calibration on the FSR sensor before the experiments. As shown in the Table 3, the values of grasping force were 1.06[N] for the 12-layer small-scale, 1.06[N] for the 10-layer medium-scale, and 1.35[N] for the 10-layer large-scale. Above these values, the devices slipped and deviated from the FSR sensor. Note that the experimental results may be rough values due to the different contact area between the FSR sensor and the device.

TABLE 3. Device evaluation results of production time and force performance.

Scale	Production time [min]	Max lifting force [N]	Max grasping force [N]
Small	(6 layer) 52	(6 layer) 5.9	(12 layer) 1.06
Medium	(10 layer) 43	(10 layer) 2.7	(10 layer) 1.06
Large	(10 layer) 40	(10 layer) 2.0	(10 layer) 1.35

VII. DISCUSSION

Conventional robotic arms made of rigid materials usually require complex mechanical parts, which may make it time-consuming and labor-intensive to design and fabricate such devices. On the other hand, origami structures can be fabricated by folding thin materials with low material and fabrication costs. We believe lightweight and foldable wearable devices can be useful in assisting with tasks in our daily lives. The user can wear such lightweight devices comfortably for extended periods of time without fatigue. In addition, mobility and convenience can be improved, as the user burden is minimized when carrying the device around. A foldable design has the advantage that the device need only be deployed when in use and can be compactly stored at other times. This foldable structure makes efficient use of space without disturbing the user. Foldable devices also offer the advantage of being easy to transport. Therefore, the proposed SRLs devices with these characteristics can support a variety of tasks in everyday life and with applications in many scenarios. The advantages of scalable devices can be exploited not only for adapting them to different applications but also for fine-tuning them to the differences in the physique of each user. For example, arm length and wearing position can be adjusted to meet different physical needs. This scalable structure allows the device to be customized to the individual requirements of the user, which not only provides comfort but also has the effect of minimizing the burden on the body and optimizes usability in different environments.

One limitation of this work is that origami fatigue is an issue. Our experiments verified that polypropylene can reduce such fatigue, although it may eventually occur after prolonged use. Due to the low production cost, this issue can be solved by re-fabricating the origami structure. However, the production of the proposed SRLs requires a long time to hand-fold and a short fatigue life, which places a burden on the user. In addition, the proposed SRLs may lack payload capacity and accuracy and are limited to less demanding tasks. The small output of the proposed SRLs means that it can only manipulate objects of small weight, which greatly limits its range of applications. A solution to these challenges is the use of pneumatic actuators. In previous studies, the combination of origami structures and pneumatic actuators has resulted in high output, long fatigue life, and rapid manufacturing [39], [40]. Therefore, applying pneumatic actuators to the proposed method is one of the important research directions for future works. It should be noted that the twisted tower structure has the property of torsion, which can cause unexpected behavior, especially if torsional behavior occurs during bending operations. Although the size may be freely adjusted in the design interface, physical constraints exist during the actual assembly phase. In particular, it is difficult to fold sizes that are too small during the hand-folding process. The size of the motor is another constraint to making a compact design. If the motor is too small, the risk of being unable to provide the required torque may be a consideration. In addition, the lengths of twisted tower structures must be designated in discrete values because of layer construction constraints.

VIII. CONCLUSION

In this study, we developed scalable and foldable SRLs using origami-inspired structures. By employing a design interface and laser cutting techniques, the origami structure can be fabricated with scalability and stretchability at a low cost. From our material experimentation, it was verified that the origami structure made of polypropylene exhibited the highest durability. Additionally, varying the number of layers revealed that an increase in layers led to decreased rigidity. We leveraged the proposed scalable origami module for SRLs to select a suitable scale depending on the application scenarios. In addition, the proposed foldable mechanisms enable safe use without interfering with the user's movements. The lightweight and flexible materials used in the proposed devices provide a high-quality experience for various users in their different applications. We believe that the combination of soft robotics and wearable devices will play an important role in human augmentation applications.

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