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DEVELOPMENT OF A NEGATIVE-PRESSURE-DRIVEN SOFT LINEAR ACTUATOR FOR FIXATION PART OF WEARABLE ASSISTIVE DEVICES

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In the study, we propose a negative-pressure-driven soft linear actuator for the fixation part of an exoskeleton. In the study, a concept of the fixation part that is easy to wear with reliable force transmission is first proposed. Subsequently, a negative-pressure-driven soft linear actuator for the proposed fixation method is introduced and prototyped. Finally, basic characteristic experiments are conducted with a prototype. The results indicate that decreases in the pressure increase the actuator's contraction force and maximum contraction. It exhibits a large hysteresis that is approximately 50% at maximum contraction force. Increases in the width increase the contraction force. Increases in the height increase the force and rate of contraction.

1. Introduction

Recently, the burden on workers is expected to increase due to the declining birth rate and aging population. A solution to the problem is an assistive exoskeleton that assists human movements [1-4]. In an assistive exoskeleton, it is important to stably transmit the assistive force of the actuator to the wearer. Existing fixation methods can be divided into two groups. The CYBERDINE HAL uses a method of wrapping a belt and fixing it with a hook-and-loop fastener [1]. In the case of assistive orthosis manufactured by Meiji University, the shape of the wearer's leg is considered and the fixation part is cast by using the wearer's shape [2]. Although the former is easy to wear and is low cost, it tends to slip and the transmission of the force can become insufficient. Conversely, the transmission of force is reliable in the latter. However, it involves significant manufacturing time because it is made to order.

Therefore, the aim of the study is to develop a fixation method that achieves easy attachment and detachment and reliable force transmission. In a previous study [5], we proposed a fixation method using a jamming transition that can deform based on the body shape. Additionally, we conducted a sensory evaluation experiment and compared the existing fixed part with the prototype fixed part. Sensory evaluation experiments confirmed that the discomfort was almost identical to that of the existing fixed part, and that the fit was better when compared to that of the existing fixed part. However, the fixation part using the jamming transition required two pneumatic systems, namely positive air pressure and negative pressure generation. Thus, installation was difficult and the system was complicated.

In the study, we propose a negative pressure-driven linear actuator for the fixation part to simplify the fixing operation. First, we propose a fixed part using a negative-pressure-driven actuator. A prototype is then developed. Finally, the characteristics of the proposed actuator are investigated.

2. Concept of fixation part and soft negative-pressure-driven linear actuator

2.1. *Concept of fixation part*

Figure 1 shows the structure of the proposed fixation part. The structure consists of a frame, a jamming layer, and an actuator. First, the body is passed through the fixation part, and the end of the jamming layer is pulled with the actuator to fit the layer to the body. Subsequently, a negative pressure is applied to the jamming layer and the layer hardens. The jamming transition is a phenomenon in which the powder behaves like a solid when the density of the aggregate of particles exceeds a certain threshold and behaves like fluid when the density falls below the threshold [6]. In the aforementioned operation, the fixed part is quickly transformed into a shape that follows the body shape.

In extant studies [5], the method was compared with the existing belt type via sensory evaluation experiments, and the results indicated superiority in terms of wearing feelings. However, a positive pressure-driven actuator was used for the actuator, and thus two systems of pneumatic circuits (i.e., positive pressure and negative pressure) were required and resulted in complicated operation and structure. In the study, we propose a negative-pressure-driven soft linear actuator to drive this actuator with the same negative pressure as the jamming layer.

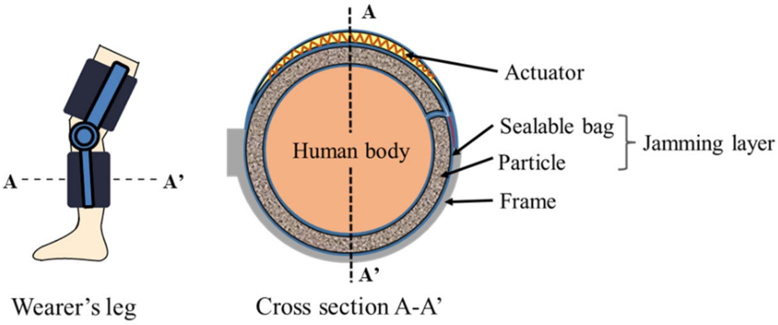

Figure 1. Structure view of the proposed fixation method

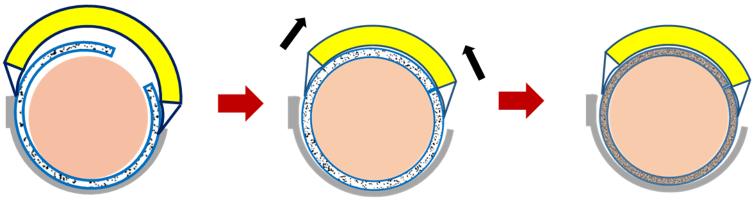

Figure 2. Movement of the proposed device where the body is passed through the fixation part (left), the end of the jamming layer is then pulled with the actuator such that the layer fits the body (middle). Finally, a negative pressure is applied to the jamming layer, and the layer hardens (right).

2.2. *Required specifications of the actuator*

The actuator used for the fixation part is required to satisfy the following requirements.

- Shape adaptability to fit the body shape
- Light weight
- Tightening force of 10 to 15 N
- Maximum contraction ≥ 40%

With respect to the tightening force, we referred to the results of the preliminary experiment. In the experiment, we subjectively measured the upper limit range of the tightening force that does not feel uncomfortable. The target contraction rate is set to satisfy parts such that hands and feet pass through the fixed part. Specifically, in the case of the fixation of the calf, the perimeter of the calf approximately corresponds to 180 mm and that of the foot approximately corresponds to 300 mm. Therefore, a contraction rate of 40% is required to fit the fixation part after the foot part passes through.

2.3. *Soft negative-pressure-driven linear actuator*

To develop an actuator that satisfies the requirement in section 2.2, we focus on fluid-driven origami-inspired artificial muscles [7] from Harvard University. The actuator is composed of a zigzag thin plate skeleton and outer membrane, and it contracts when it is folded by negative pressure. It is characterized by high shrinkage, flexibility to handle curved surfaces, and light weight.

However, the actuator is not suitable for the fixation part because it generates a sudden contraction force when negative pressure is applied, and there is a possibility of significantly tightening the human body. Therefore, we propose the actuator shown in Figure 3. The change in the contraction force in response to pressure changes is moderated by inserting a sponge between the folded structures. Figure 4 shows the prototype actuator.

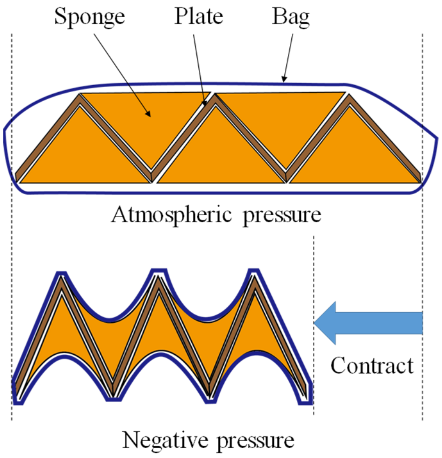

Figure 3. Moving principle of the proposed actuator

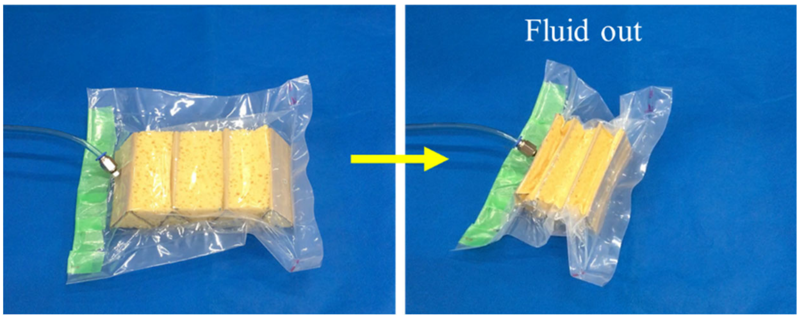

Figure 4. Prototype of the actuator

3. Basic characteristic experiment

3.1. *Parameters of the actuator*

Five prototypes of actuators with different parameter values were prototyped. The number of sponges sandwiched between the plates and length of the base of the isosceles triangle of the sponge cross-section corresponded to 40 mm. The ratio of the width and height of the sponge cross-section of each actuator is shown in Fig. 5 and is expressed as follows:

(1) width ②: ①: ③ = 1: 2: 3
(2) height ④: ①: ⑤ = 1: 2: 3

Table 1 shows the cross-sectional dimensions of each actuator. In the figures, the thickness of the plates was ignored.

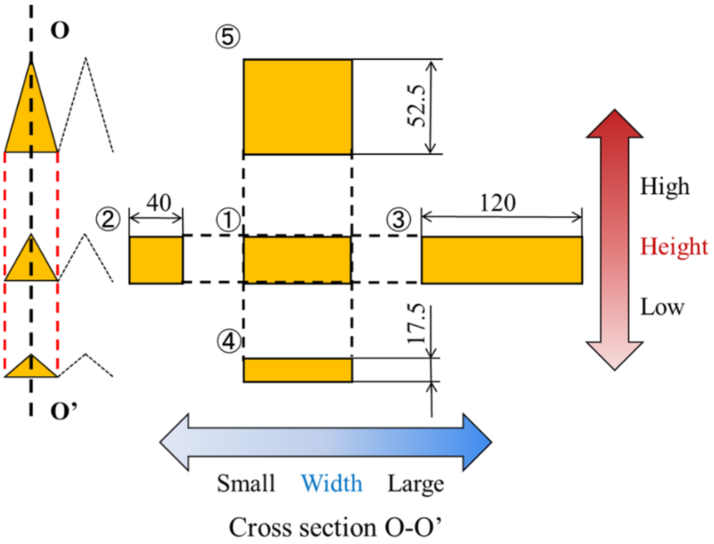

Figure 5. Variable parameters of the prototypes

Table 1. Parameters of the prototypes

Actuator	Height[mm]×Width[mm]	Length[mm]
□	35×80	165
□	35×40	185
□	35×120	180
□	17.5×80	170
□	52.5×80	185

3.2. *Method*

Figure 6 shows the configuration of the experimental setup, and Fig. 7 shows a picture of the experimental setup. The actuator was placed horizontally and an end was fixed. The compressor was connected to the ejector via a regulator and a 2-port valve. A negative pressure was generated by the ejector, and the actuator was activated. The pressure supplied to the actuator was maintained as constant, and the contraction force and contraction rate were measured. The speed controller was slightly open to the atmosphere to suppress the pressure fluctuation due to changes in the volume of the actuator. The contraction force was measured via a digital force gauge (Nihondensan Shinpo FNG-2). The displacement of the actuator was measured via a ruler, and the pressure was measured using a pressure sensor.

In the experiment, a load was first applied to the actuator from the maximum contracted state until the actuator no longer expanded under a certain pressure. Subsequently, the load was decreased until contraction stopped. The minimum pressure was set to the pressure value at which the shrinkage ratio was saturated, and the pressure value was set to three values, namely two thirds and one third of the minimum pressure value.

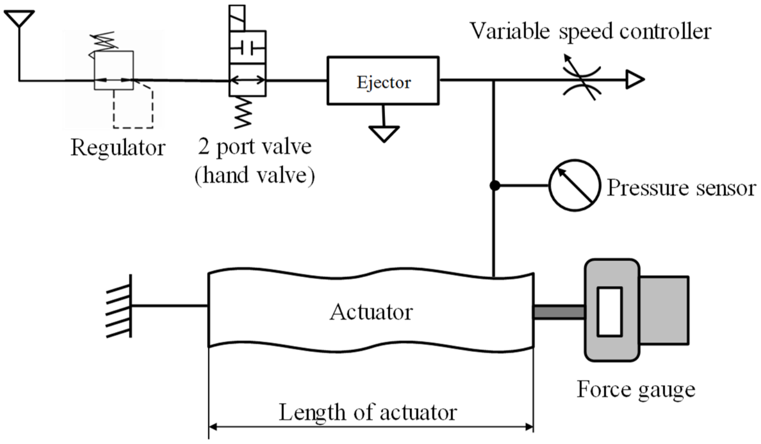

Figure 6. Schematic diagram of the experimental set up

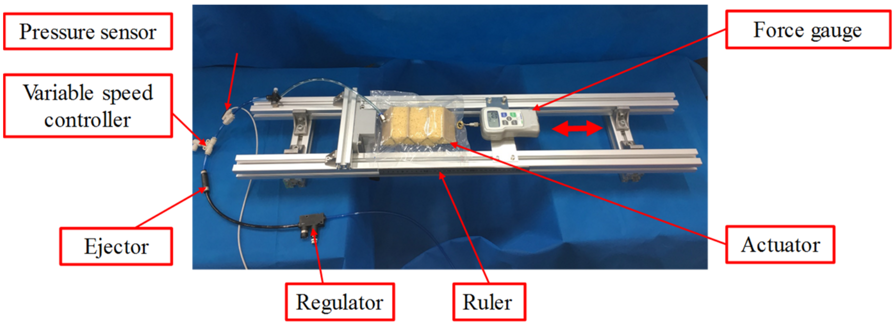

Figure 7. Experimental set-up

3.3. *Results and discussion*

Figures 8–12 show the experimental results. The lower right shows the starting point of the measurement, external force is applied to the upper left, and the external force then decreases. It is noted that the horizontal axis denotes the contractive rate (not the amount of contract or actuator length). The results indicated that decreases in the applied pressure increased the contraction force and contraction rate. Additionally, it was confirmed that the hysteresis of the actuator was high.

The maximum contraction of actuator ① under no load in Fig. 7 corresponded to 52.5% at −36 kPa. This equates to a contraction of 85 mm. At −24 kPa, the shrink force was approximately 13 N when the shrinkage corresponded to 40%. Therefore, the actuator satisfied the requirements for the fixation part. At −12 kPa, the no-load shrinkage corresponded to 39.8%.

The jamming layer was considered as unable to fit to the body at –12 kPa because the contractive force at 40% contraction was approximately zero.

In the results of ①, ②, and ③ , the actuator width was varied. Figures 8–10 show the measurement results of the actuators. Thus, it was confirmed that the maximum contraction did not significantly change with width. This was because the change in width corresponds to the case where the actuators are connected in parallel. Therefore, the force at the same shrinkage was linear with respect to length.

The results in ①, ④, and ⑤ in which the height of the actuator is varied were considered. It was confirmed that increases in the height increased the maximum contraction and contractive forces. This was because the height directly affects the area of atmospheric pressure.

Overall, decreases in the pressure increased the actuator's contraction force and maximum contraction. It exhibited a large hysteresis of approximately 50% at maximum contraction force. Thus, increases in the width increased the contraction force. Increases in the height increased the force and rate of contraction.

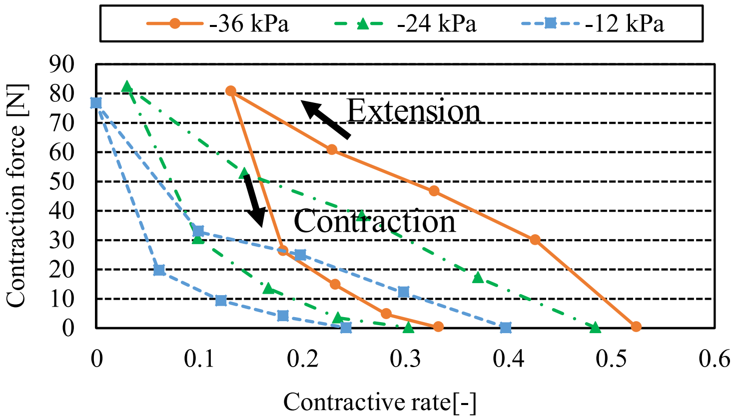

Figure 8. Contraction force and contraction of the H35-W80 actuator

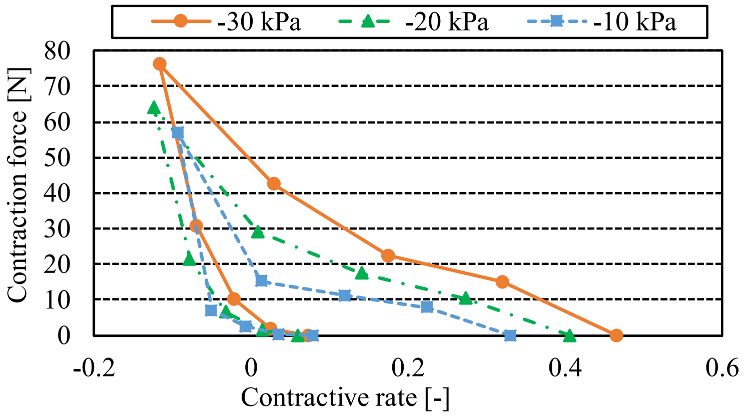

Figure 9. Contraction force and contraction of the H35-W40 actuator

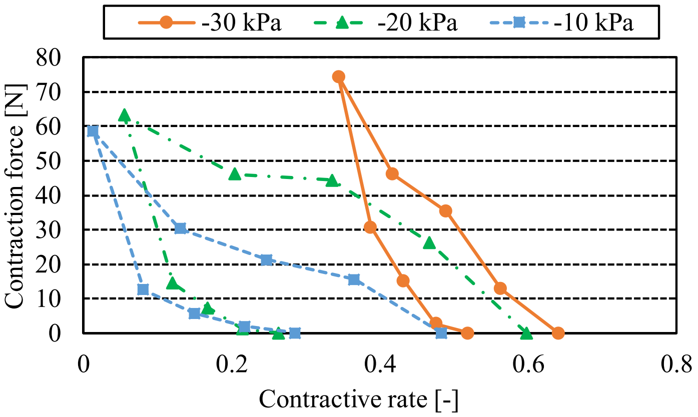

Figure 10. Contraction force and contraction of the H35-W120 actuator

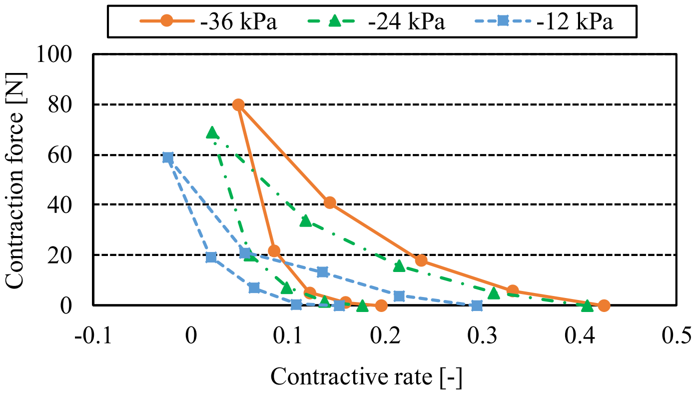

Figure 11. Contraction force and contraction of the H17.5-W80 actuator

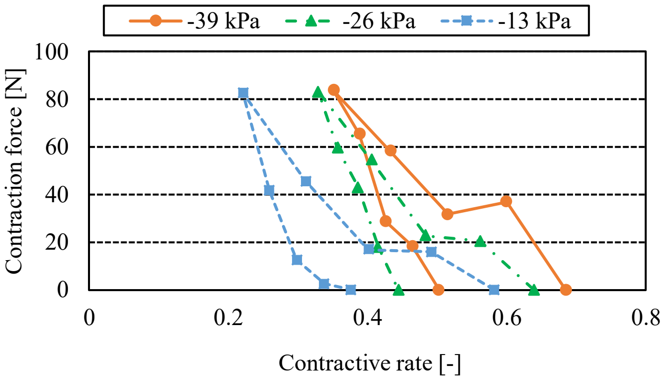

Figure 12. Contraction force and contraction of the H52.5-W80 actuator

4. Conclusion

In the study, a negative-pressure-driven soft linear actuator for the fixation part of an exoskeleton was proposed. The actuator was prototyped, and the basic characteristics were experimentally investigated.

A fixation part that uses an actuator and a jamming layer will be developed and tested in a future study.

Acknowledgments

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