Proceedings of the 6th JFPS International
Symposium on Fluid Power, TSUKUBA 2005
November 7-10, 2005

SHAPE STABILIZER USING AN ARTICULATION-TYPE PASSIVE ELEMENT

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ABSTRACT

An articulation-type passive element is a planate bag containing articulating thin plates. It can be freely contracted and bent to fit an arbitrary rounded surface. Evacuation of the internal air renders the bag rigid so that it maintains whatever shape it has been given. The stiffness of the articulation-type passive element is proportional to the reduction in internal pressure below atmospheric pressure. Experimental results show that the stiffness is higher and more stable than that of other passive elements that function by vacuum pressure. As an application of the new passive element, we developed an orthopedic cast that is easy to remove or change in shape. The passive element is also applicable to wearable force displays. Passive elements fixed on an operator provide a sensation of reaction force by constraining his or her motion. The new passive element is suitable for wearable mechanisms, by virtue of being lightweight, soft, and safe.

KEY WORDS

Wearable robot, Passive element, Medical and Welfare Equipment

INTRODUCTION

Wearable robots for assisting human motion must be lightweight so as not to impose a burden on the wearer. They also must be soft so as not to obstruct various motions made by the wearer. Lastly, they must be safe so as not to injure the wearer when they are broken. In view of these requirements, conventional robots composed of electric motors and metal frames seem unsuitable. Since pneumatic actuators such as rubber actuators are soft and lightweight as compared with electric motors, wearable robots employing pneumatic actuators have been developed [1-5]. However, these robots also involve a risk of exerting excessive force when they are broken. We have developed some wearable robots that employ passive elements. For example, fixing knee joints by passive elements lightens the load of lower limbs for supporting body weight [6]. Adding resistance to hand motion by passive elements fixed on the hand provides the wearer with a sensation of touching an object or of moving water with viscosity [7]. These wearable robots work as inherently passive systems that never exert excessive force in the event they malfunction. In this paper, we examine a novel passive element called an articulation-type passive element. It can be freely contracted and bent to fit an arbitrary rounded surface. Evacuation of the internal air renders the element rigid so that it maintains whatever shape it has been given. We have developed several types of passive elements that function by vacuum pressure [8]. The new passive element has higher and more stable stiffness than do other, previously developed passive elements. The structure and mechanical properties of the element will be described in this paper.

Structure of the articulation-type passive element

Figure 1 depicts the structure of the articulation-type passive element. A planate bag contains articulating thin plates, which are bound by wires through rectangular holes formed in the plates. Each plate can rotate about the rectangular hole and slide. By combining the rotation and sliding, the element can be contracted and bent as shown in Figure 2. As shown in Fig. 3, the element also forms a curved surface by rotation and the sliding of the plates. The bag containing the articulated thin plates is made of a vinyl film, which is easily bent but cannot be lengthened. The thin plates are made of plastic. When the inside air is evacuated, atmospheric pressure compresses the thin plates, and the plates motions are locked into an arbitrary shape by friction. Stiffness can be adjusted by varying the internal pressure.

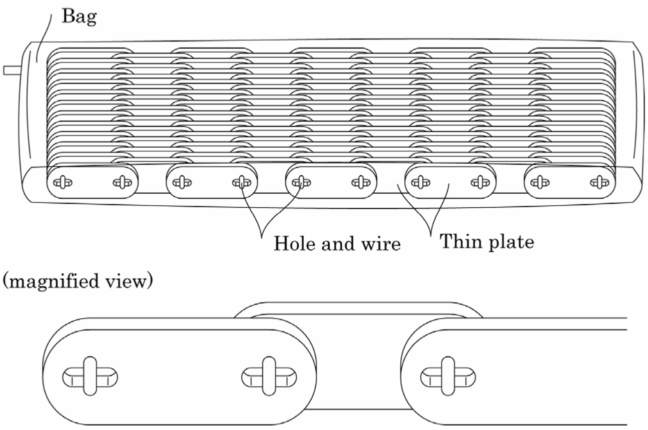

Figure 1 Structure of the articulation-type passive element.

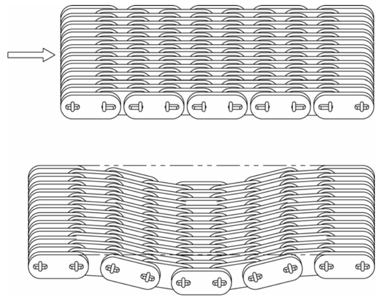

Figure 2 Contraction and bending.

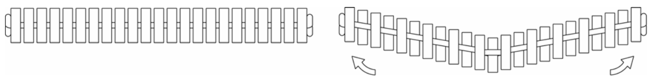

Figure 3 Bending along the connection wires.

Mechanical properties of the articulation-type passive element

Factors of stiffness

The stiffness of the articulation-type passive element is produced by the friction of the stacked plates and the elasticity of the covering film. The constraint torque exerted by the friction force on the plates can be expressed by

$$T = -\frac{1}{2} n \mu P \pi r^3 \tag{1}$$

where

T Constraint torque
n Number of stacked plates
μ Friction coefficient
P Gauge pressure
r Radius of the contact circle area on the plates.

The stiffness produced by the covering film is affected by the elasticity, the friction between the covering film and the plates, and the size of the covering film.

Experimental setup

In order to examine mechanical properties, we measured the stiffness of articulation-type passive elements. All articulation-type passive elements measured in the following experiments were composed of Polyester plates. Figure 4(a) depicts the size of a plate. The thickness of the plate is 0.188[mm]. Ten plates were articulated in series, and 50 to 150 plates were stacked and bound by plastic wires. One edge of the articulation-type passive element was fixed, and the adjacent plate was pushed to rotate around the hole on the fixed plate. The reaction force and the displacement were measured during this operation. Stiffness is affected by the distance of neighboring plates, because the distance correlates with the contact area on the plates. The distance was set to the maximum in the following experiments. Therefore, the stiffness measured in the following experiments is expected to be minimum. The distance between the point of pushing and the axis of rotation was 13[mm].

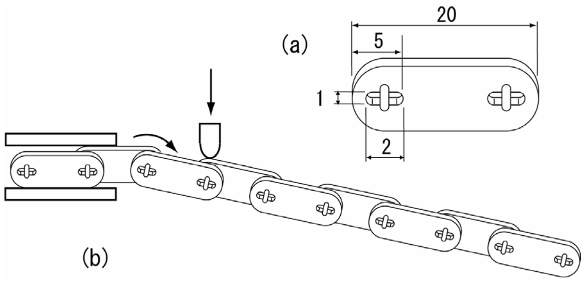

Figure 4 (a) Size of a plate (b) Experimental setup.

Effect of inside air pressure

Figure 5 shows the stiffness of an articulation-type passive element at various inside air pressures. The covering film of the passive element was urethane having a thickness of 0.2[mm]. Fifteen articulated plates were stacked and bound by wires. Therefore, the passive element consists of 150 plates. Figure 6 shows the relation between reaction force at various translations and internal air pressure. Stiffness was proportional to the reduction in internal pressure below atmospheric pressure. However, stiffness at 0[kPa] is almost zero. This characteristic indicates that the stiffness of the articulation-type passive element can be controlled by the internal air pressure.

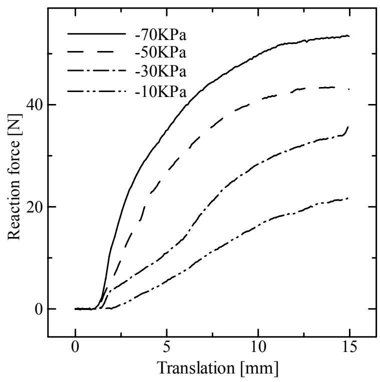

Figure 5 Stiffness at various internal air pressures.

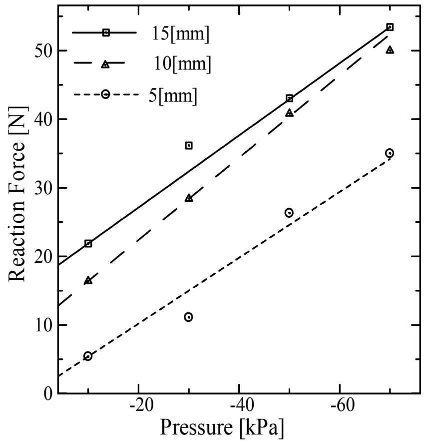

Figure 6 Relation between stiffness and internal air pressure.

Effect of number of stacked plates

Figure 7 shows stiffness of the articulation-type passive elements, consisting of 50, 100, and 150 stacked plates, at -70[kPa]. The width of the passive element was 10, 20 or 30[mm]. The covering film was urethane having a thickness of 0.2[mm]. Figure 8 shows the relation between the number of stacked plates and stiffness of the passive element. Stiffness is proportional to the number of stacked plates; this relation coincides with the theoretical expression of constrained torque shown in Eq.(1). However, the effect of the number of stacked plates should be examined in isolation from the effect of the covering film, since the covering films of these passive elements differ in thickness. The analysis will be described in the following section.

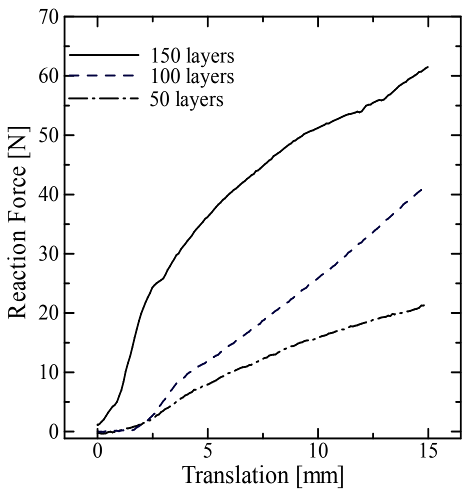

Figure 7 Stiffness of the passive elements, consisting of various numbers of stacked plates.

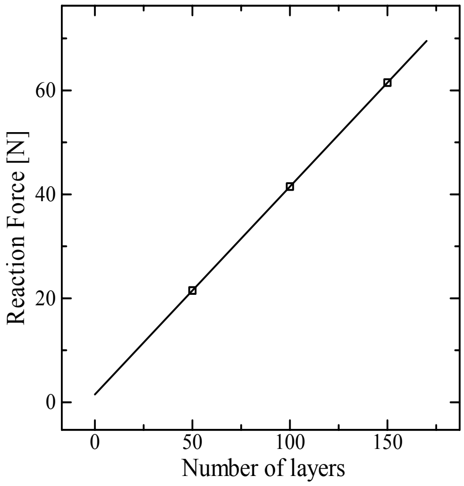

Figure 8 Relation between number of stacked plates and stiffness.

Effect of the covering film

Figure 9 shows stiffness of passive elements composed of various covering films. The materials of the covering films are urethane (thickness 0.2[mm]), rubber (thickness 0.3[mm]), cloth-coated vinyl (thickness 0.2[mm]), and vinyl (thickness 0.1, 0.2, 0.3[mm]). Figure 10 shows elongation stiffness of these covering films. The measured covering films have a width of 10[mm] and a length of 50[mm]. These figures indicate that stiffness of the passive elements correlates with the elongation stiffness of the covering films.

To dissociate the effect of covering film and the brake torque of stacked plates in stiffness of the passive element, we used two methods to estimate the stiffness produced by the covering film. The first method estimates stiffness from the elasticity of the covering film. The elongated length is estimated geometrically, under the assumption that the covering film does not slip on the thin plates. The second method estimates stiffness from observation of stiffness at various internal air pressures (Figure 11). Since the linear relations between stiffness and internal air pressure have their intercepts at 0[kPa], we assume that these intercepts represent stiffness produced by the covering film. Note that actual stiffness at 0[kPa] is almost zero. Figure 12 compares values of stiffness estimated by the two methods. Over the entire range depicted, the two estimates are almost identical. Figure 13 shows the breakdown of stiffness of the passive elements. The estimated brake torque was derived by subtracting the stiffness produced by the covering film from total stiffness of the passive elements. Estimated brake torque was almost identical, with the exception of the elements covered by thick vinyl sheets.

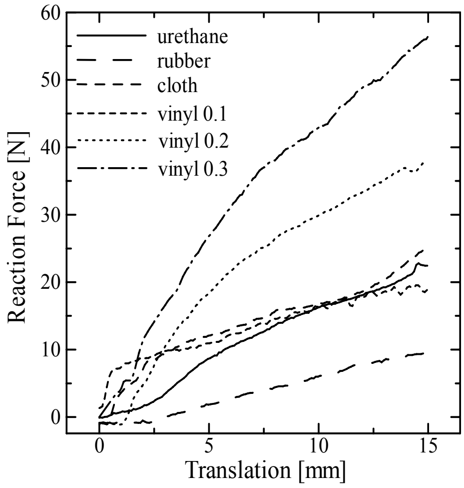

Figure 9 Effect of the covering film.

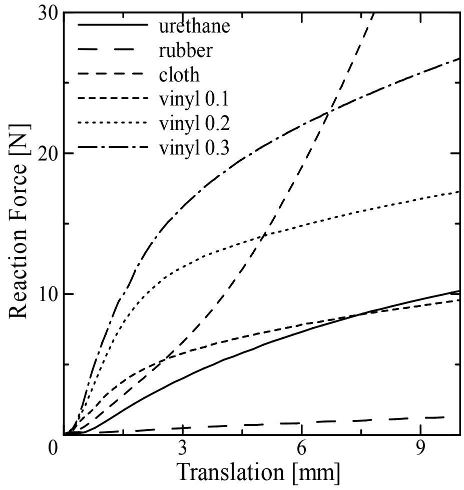

Figure 10 Elongation stiffness of covering films.

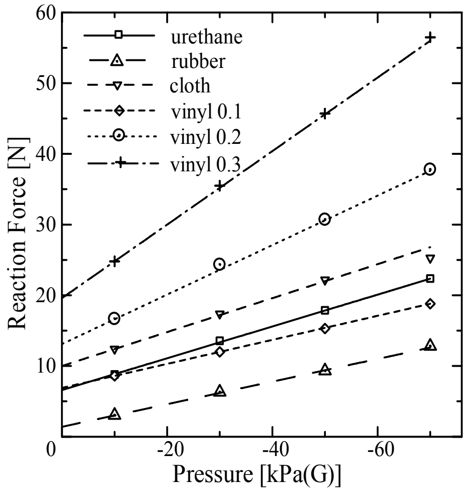

Figure 11 Relation between stiffness and internal air pressure.

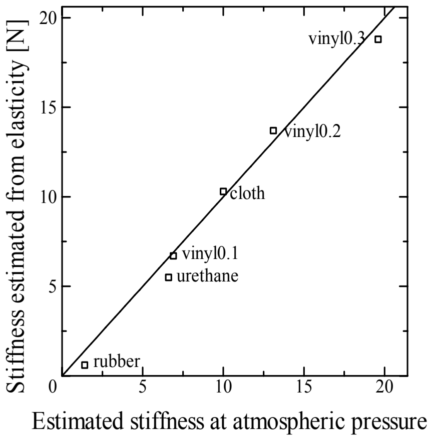

Figure 12 Stiffness values estimated by two methods.

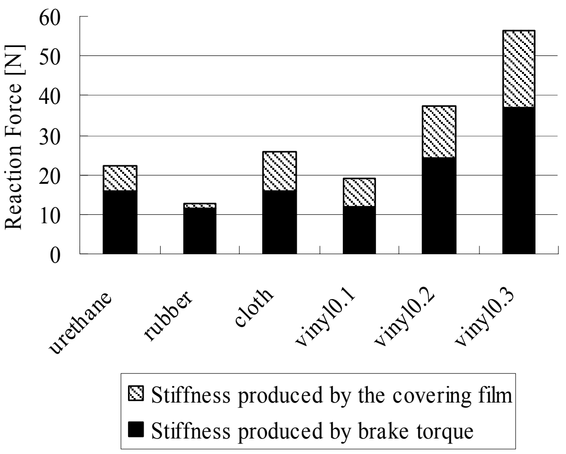

Figure 13 Breakdown of stiffness.

Reusable cast composed of articulation passive elements

Structure of the reusable cast

We developed a reusable orthopedic cast as an application of the articulation-type passive element. Conventional casts are made rigid by chemical reaction with water. Once it becomes solid, a conventional cast can be removed only by cutting with a grinder. The cutting process is unpleasant for patients. The cast developed from the articulation-type passive element is made rigid by evacuating the inside air. It is reusable, and shape and stiffness can be adjusted by the internal air pressure.

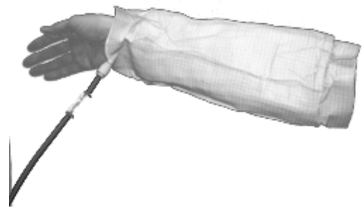

Figure 14 Reusable cast composed of articulation-type mechanical constraint.

Figure 14 shows a reusable cast developed from articulation-type passive elements. Twenty plates are articulated in a circular pattern, and 1,400 sets of such circularly-arranged plates are stacked and bound by wires. The cast is composed of 28,000 thin plates in total. Total weight is 566[g]. Maximum diameter is 85[mm], and overall length is 220[mm]. The diameter is adjustable, owing to the translational freedom of each articulation. The wrist portion of the cast shown in Figure 14 is contracted for fitting the surface to the skin. Minimum diameter is 60[mm].

Reusable cast composed of particle mechanical constraints

Particle mechanical constraint is another passive element, which we developed previously. It is a bag containing beads. It can be changed in shape, and evacuation of the inside air renders the bag rigid so that it maintains whatever shape it has been given. We also developed a reusable cast using the particle mechanical constraint, in order to compare stiffness with that of the cast composed of the articulation-type passive element. Figure 15 depicts the structure. The torus-shape cloth tubes containing beads are connected to form a cylinder. The cylinder is enveloped by a cloth-coated vinyl sheet. Stiffness of the particle mechanical constraint correlates with the material of beads. We developed two reusable casts using Styrofoam beads and nylon shots. The diameter and length are the same as those of the cast developed from the articulation-type passive element. Both casts have a thickness of 10[mm]. The weights of these casts were 312[g] and 70[g], respectively.

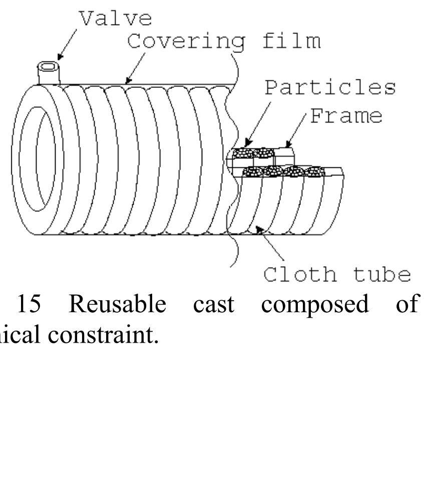

Figure 15 Reusable cast composed of particle mechanical constraint.

Evaluation of stiffness

We examined stiffness of the casts developed from the various passive elements described above. We also examined the stiffness of a conventional, commercially available cast. Figure 16 shows the relation between reaction force and compression ratio when a testing machine compressed the center of the casts by a circular plate. The outer diameter of the plate was 200[mm]. The cast developed from the articulation-type passive element had greater stiffness than that developed from particle mechanical constraints. It also had a greater stiffness than the conventional cast below 300[N]. However the stiffness of the articulation-type passive element gradually declined with increasing reaction force, because the stiffness is exerted mainly by friction force. The necessary stiffness of orthopedic casts is not clear because there are many types of use. The stiffness of the articulation-type passive element is not enough to guard an arm from accidental collision, though the stiffness is enough to fix an arm.

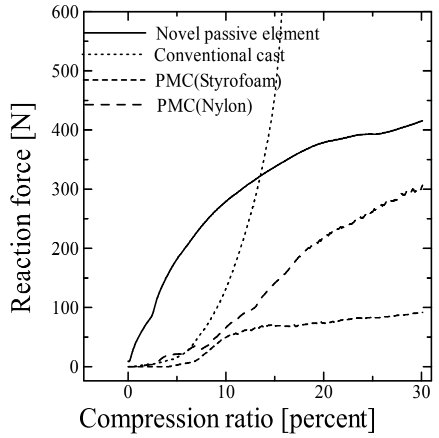

Fig. 16 Stiffness of four different casts.

Conclusion

This paper describes a novel passive element that can be freely contracted and bent to fit an arbitrary rounded surface. A reusable cast developed from this passive element shows higher stiffness than a reusable cast developed from particle mechanical constraints. The cast also shows higher stiffness at small compression force than a commercially available cast. Reduction in thickness and weight is a problem to be solved for practical use. The problem correlates with the stiffness of the passive element. We are investigating better materials for the plates and the covering film in order to increase stiffness of the passive element. This passive element is applicable also for haptic displays and wearable robots for assisting human motion. Development of such applications is the subject of our future studies.

Acknowledgments

This study was completed with the assistance of the 2004 Industrial Technology Research Grant Program of the New Energy and Industrial Technology Development Organization (NEDO).

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