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McKibben artificial muscle using shape-memory polymer

Kazuto Takashima[a,b,*], Jonathan Rossiter[a,c], Toshiharu Mukai[a]

[a] RIKEN-TRI Collaboration Center for Human-Interactive Robot Research, Advanced Science Institute, RIKEN, 2271-130 Anagahora, Shimoshidami, Moriyama-ku, Nagoya 463-0003, Japan
[b] Graduate School of Life Science and Systems Engineering, Kyushu Institute of Technology, 2-4 Hibikino, Wakamatsu-ku, Kitakyushu 808-0196, Japan
[c] Intelligent Systems Research Group, Department of Engineering Mathematics, University of Bristol, University Walk, Bristol BS8 1TR, UK

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ABSTRACT

When McKibben artificial muscle actuators are used to drive robotic joints, they are typically configured in pairs which act antagonistically to increase joint stiffness. However, this configuration cannot maintain a fixed position without continuous control. The objective of this study is to develop a McKibben artificial muscle which can fix into a rigid shape without the need for continuous control. This is achieved by exploiting the inherent properties of shape-memory polymers (SMPs). SMPs can be deformed above their glass transition temperature (T_g) upon the application of a small load. They can maintain their shape in a rigid form after they have been cooled to below T_g. When heated again above T_g, they return to their predefined shape. Exploiting these characteristics, we impregnate the braided mesh shell of a commercial McKibben artificial muscle with SMP resin. When this new actuator is warmed above T_g, it can be used as a conventional McKibben muscle. When the actuator attains its desirable length, it can be cooled to below T_g and the SMP will fix the structure in a rigid, actuated, state. This state is maintained without the need for any air supply or control system. The enhanced versatility of this new actuator is shown through a series of experiments conducted on a prototype SMP McKibben actuator.

1. Introduction

In rapidly aging societies, such as Japan, robot technologies have received a large amount of attention because of their potential to overcome the physical degradations that come about through the natural aging process. Proposed solutions include robots that directly supplement the body's remaining muscles, for example through wearable power assist suits [1–5], and robots that act as ‘helpers’ in activities that are particularly difficult, such as getting out of bed [6,7]. In many of these applications, pneumatic actuators, such as the McKibben artificial muscle [1–3,8–11], are favored over electric motors because of their light weight, flexibility, large output and back-drivability.

As shown in Fig. 1, the McKibben-type pneumatic actuator has a simple structure consisting of an internal bladder (e.g., rubber tube) wrapped in a braided mesh shell with flexible yet non-extensible threads (e.g., nylon or fiberglass mesh). The actuator has a fitting attached at one end through which the internal bladder is pressurized. When a positive air pressure (with respect to atmospheric pressure) is introduced to the bladder, it expands. Braided mesh shell is radially deformed and, resembling the Chinese finger puzzle and a pantograph, the mesh changes configuration in a scissor-like action due to the non-extensibility of the threads. This action resolves the radial expansion forces into axial contraction forces. The result is a shortening of the whole actuator if it is unloaded or the generation of a significant axial force if a mechanical load is attached.

When these actuators are applied to robotic joints, the joints are typically driven by pairs of actuators located antagonistically to increase the joint stiffness. The actuator can be considered as a simple spring-like elastic element, or a “gas spring,” whose stiffness is proportional to the inner pressure [8]. Since the actuator is effectively a spring, the shape fixity of the actuator is low. Here we define *shape fixity* as the ability of an actuator to maintain its actuated state against external forces without energy consumption. Moreover, even with active control the ability of the McKibben actuator to maintain a fixed state under varying external forces is non-trivial because of its nonlinear characteristics and hysteresis. In this study, we propose a new pneumatic actuator based on the McKibben actuator which has enhanced shape fixity properties. This is achieved by the use of a shape-memory polymer to modulate the stiffness, and hence control the deformations, of the braided mesh shell.

2. Shape-memory polymers

As shown in Fig. 2, shape-memory polymers (SMPs) [12–23] are often described as two-phase structures comprised of a hard

* Corresponding author. Tel.: +81 52 736 5867; fax: +81 52 736 5868.
E-mail addresses: ktakashima@life.kyutech.ac.jp (K. Takashima), Jonathan.Rossiter@bristol.ac.uk (J. Rossiter), tosh@nagoya.riken.jp (T. Mukai).

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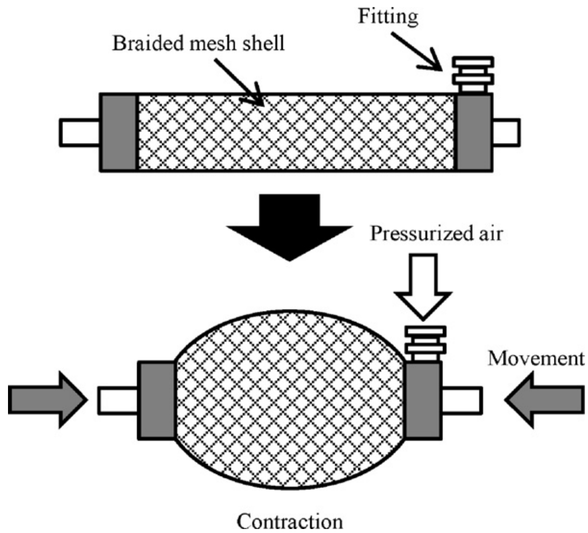

Fig. 1. McKibben artificial muscle.

(fixing) phase and a soft (reversible) phase. The hard and soft phases represent two elastic moduli: one in the lower-temperature, higher-stiffness "glassy" plateau and the other in the higher-temperature, lower-stiffness "rubbery" plateau. The reversible change in the elastic modulus between the glassy and rubbery states of SMPs can be as high as 500 times [12]. In other words, SMPs can be deformed above their glass transition temperature (T_g) by applying a small load. They maintain their shape after they have been cooled below T_g and can be considered rigid in this state. When next heated above T_g, they return to the predefined shape and hence exhibit shape recovery. In many SMPs, the phase transition temperature is close to room temperature [13].

Compared with shape-memory alloys (SMAs), SMPs have the following advantages [14,15]:

1. low cost (1/20 of SMAs);
2. light weight (1/7 of SMAs);
3. rigidity in the low-temperature range and flexibility in the high-temperature range;
4. higher strains; greater than 400% (7% maximum in SMAs);
5. ease of creating complex 3D shapes;
6. can be dyed (dyeable).

With these features, SMPs are increasingly being investigated for use in smart materials such as those used in textiles, ergonomic utensils, spacecraft sun sails, self-disassembling mobile phones, morphing skins, intelligent medical devices, refreshable Braille displays, and implants for minimally invasive surgery [12–23].

3. Concept of the actuator

A conventional McKibben actuator can be considered as a device with only two states; *unactuated* and *actuated*. Transition between these states is controlled by air pressure. If we now modify the device by the introduction of SMPs, we introduce a second control mechanism, namely temperature control. The two control parameters of pressure and temperature mean that the actuator can exhibit more states and the complexity of the state transitions greatly increased. Fig. 3 shows five distinct states {S1, . . ., S5} and a cycle of state transitions for the proposed SMP McKibben artificial muscle. As can be seen, by a controlled application of pressure and temperature the actuator can be transitioned from state S1 into state S4 where temperature is below T_g (the SMP is rigid) and pressure is low (no compressor energy is needed). S4 is therefore a state of shape fixity. Note that the starting state S1 is also a state of shape fixity.

The integration of SMPs into a McKibben actuator can be achieved by;

i. impregnating the external braided mesh;
ii. coating the internal bladder;
iii. fabricating the internal bladder from shape memory material.

In this paper we will use method i. This is the simplest and quickest method for hand fabricating laboratory prototypes.

Typical operation of the SMP McKibben actuator involves the following control sequence (the states are those shown in Fig. 3):

- Starting in state S1, the actuator is warmed above T_g. The actuator now enters S2.
- In S2 the SMP is soft and can be deformed. When the internal bladder is pressurized, the actuator shortens and/or produces a force if it is coupled to a mechanical load. After the actuator attains its desirable length, it is cooled below T_g and the actuator enters state S3.
- In S3 the SMP is fixed in its rigid state. If the internal pressure within the bladder is released the actuator moved to state S4.

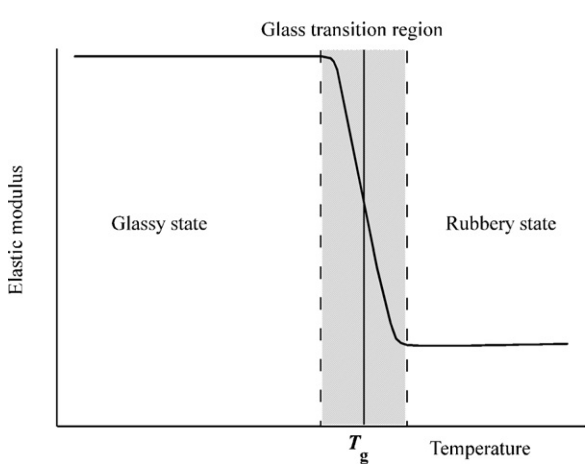

Fig. 2. Relationship between the elastic modulus and temperature of the SMP. In many SMPs, the phase transition temperature is close to room temperature.

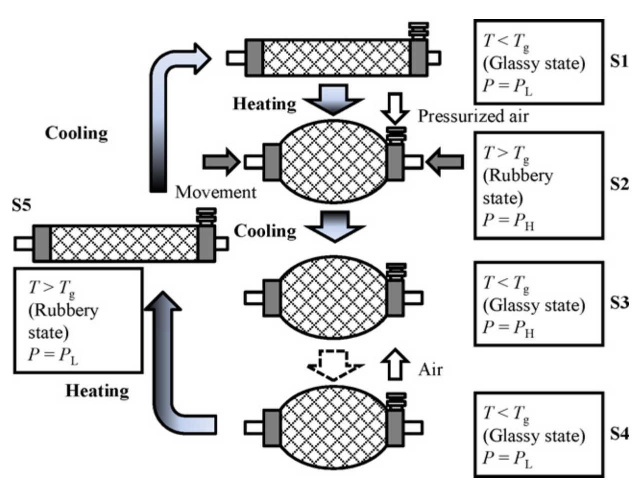

Fig. 3. Schematic representation of McKibben artificial muscle that uses SMP (P_H: high pressure, P_L: low pressure).

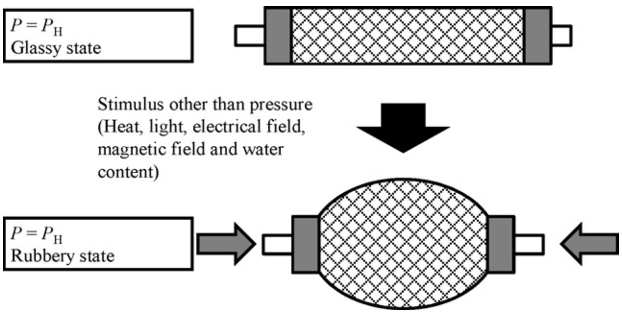

Fig. 4. Manipulation of newly developed actuators using stimuli such as heat, light, electric field, magnetic field and water content.

- In S4 the actuator maintains its length indefinitely without the need for an air supply. When the actuator is next heated above T_g, the SMP enters state S5.
- In S5 the actuator has returned to its pre-actuation state, and has exhibited shape recovery.

Compared with the conventional McKibben artificial muscle, the new actuator with SMP properties has the following advantages.

1. The actuator can be fixed more rigidly than conventional pneumatic actuators using the phase change of the SMP material. There are few other robot structures whose stiffness can be changed by such a simple mechanism [24]. The proposed soft deformable structure enables robots to have high shape adaptability and to realize sophisticated biomimetic motions that are difficult to achieve with standard McKibben actuators.
2. The actuators can achieve relatively large deformation between two rigid states.
3. The stiffness control parameter (temperature in this case) can also be used to control actuation. This can be achieved by, for example, pressurizing the actuator when the SMP is in its rigid state ($T < T_g$). When the temperature is then raised above T_g, the SMP will become soft and internal pressure will cause it to contract. This is shown clearly in Fig. 4. It should be noted that this concept can be extended to other SMP state transition stimuli including indirect heating such as illumination with infrared light, electric field, magnetic field, and lowering of T_g by water content [16].
4. The actuators can maintain a continuous desirable length.
5. Only one of the proposed actuators is needed to fix a single link in a robotic arm (see Section 6 for more details), making the actuator more suitable for miniaturization.
6. The surface area of the actuator that undergoes heating can also be controlled. If only part of the actuator is heated, only that portion of the SMP will transition to the rubbery state and hence, when internal air pressure is increased only that portion of the structure will actuate. This concept is similar to the soft robot utilizing Jamming Skin Enabled Locomotion (JSEL) [25] that utilizes jamming of a granular medium. A soft mobile morphing robot is a desirable platform for traversing rough terrain and navigating into small holes and the proposed SMP actuator provides a potential technology to enable this.

4. Methods

4.1. SMP properties

Shape-memory effects have been reported for many polymeric materials including polyurethane, polynorbornene, trans-polyisoprene, poly(styrene-block-butadiene) and perfluorosulfonated ionomers. The mechanical properties and T_g of a SMP depend on its chemical and mechanical structure [19]. In this study, we chose the polyurethane Diary shape memory polymer (DiAPLEX Co., Ltd.) because it is used in many practical applications, and T_g can be tailored within a wide range (−40 °C to 120 °C) [12–15,17,18]. Moreover, Diary has many attractive features: it is light, clear, dyeable, highly corrosion resistant, and workable [15]. In this study, we used the Diary thermoset SMP MP4510, with a T_g of 45 °C. The main characteristics of this material are summarized in Table 1.

Table 1
Characteristics of Diary SMP MP4510.

Properties	MP4510
Tensile strength ($T < T_g$) (MPa)	30
Elastic modulus ($T < T_g$) (MPa)	1350
100% tensile MD ($T > T_g$) (MPa)	4.5
Maximum elongation ($T > T_g$) (%)	>400

4.2. Prototype of actuator

To fabricate a prototype SMP pneumatic actuator we coated the braided mesh shell of a commercial McKibben artificial muscle (Shadow Robot Company Ltd. [9]) with the SMP. The prototype is shown in Fig. 5. The braid diameter and stretched length of the commercial McKibben artificial muscle are 20 mm and 210 mm, respectively [9]. These commercial actuators are normally operated using compressed air in the 0–0.4 MPa range, and the pull at 0.35 MPa is 118 N. The thermoset MP4510 SMP was processed according to the sample preparation guide provided by DiAPLEX. A and B liquid components were prepared. They were vacuum dried for 1 h, then mixed at the appropriate weight ratio. Subsequently, the commercial McKibben artificial muscle was brushed with the mixture and vacuum cured at 70 °C for 1 h. In this study, we conducted a preliminary investigation of the pneumatic behavior of this prototype through isometric and isotonic experiments.

4.3. Experimental methods

First, we verified the basic characteristics of the new actuator. In order to operate through the complete cycle of actuation shown in Fig. 3, the following characteristics must be shown:

- Shape fixity state ($T < T_g$). The actuator must be fixed rigidly and accurately in its rest position. Moreover, the actuated shape needs to be maintained for an extended period of time.
- Flexible state ($T > T_g$). The actuator must actuate effectively in its soft state.
- Cooling state ($T > T_g \rightarrow T < T_g$). The actuator can be fixed rigidly and accurately in an actuated state.
- Shape recovery state ($T < T_g \rightarrow T > T_g$). The actuator will recover its pre-programmed shape, i.e. it will return to its rest position when heated with no loading.

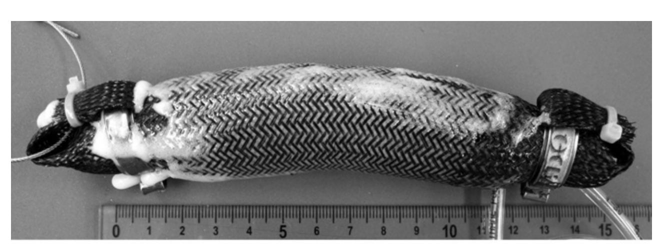

Fig. 5. Prototype of newly developed actuator with SMP.

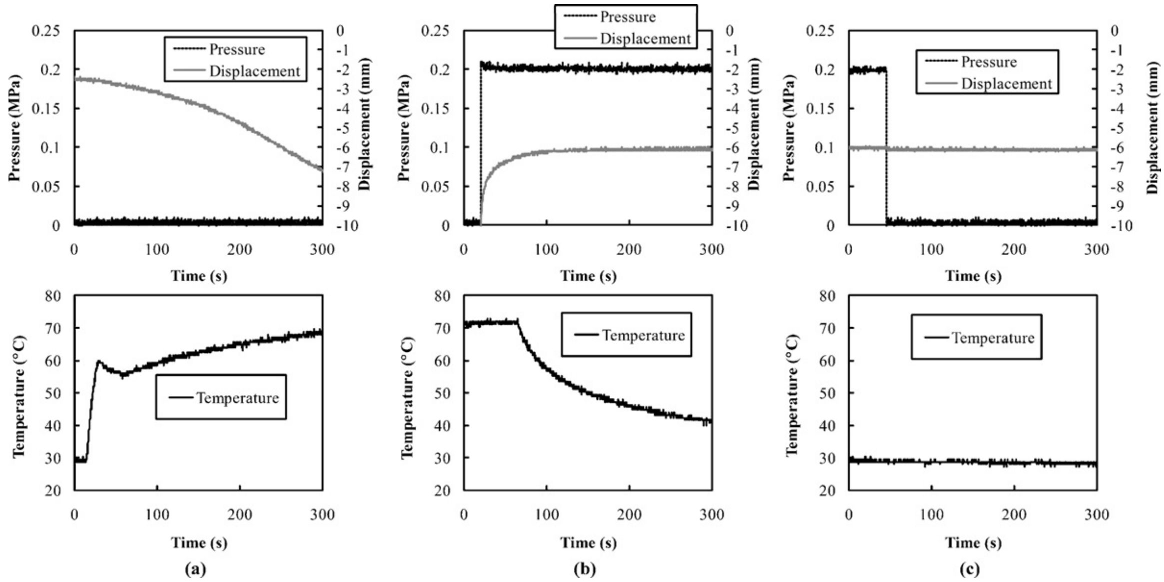

Fig. 6. Motion of the prototype actuator when the internal pressure was changed with heating and cooling under a constant load (62 N). (a) $T < T_g \to T > T_g$, $P = P_L$. (b) $T > T_g$, $P = P_L \to P_H$. (c) $T < T_g$, $P = P_H \to P_L$.

Next, we evaluated the deformation properties under the two cases of constant load (isotonic) and constant length (isometric). For comparison, an off-the-shelf McKibben actuator that was not coated with SMP was also evaluated. In the isotonic experiments, a constant weight was hung from the end of the actuators and the inner pressure was varied by supply and exhaust solenoid air valves. The displacement was measured by a laser displacement sensor (Keyence Co., LK-GD500, LK-G150). In the isometric experiments, the actuator was connected to a load cell (Kyowa Electronic Instruments Co., Ltd., LU-10KA) and the air supply was varied while the actuator length was kept constant.

Finally, we evaluated the passive deformation properties of the SMP actuator. In this way we can compare the new actuator with standard McKibben muscles which are known to have variable-stiffness spring-like characteristics, nonlinear passive elasticity and physical flexibility [8]. In these experiments, the specimen with a constant inner pressure was pulled at a constant speed (5 mm/min) and the axial loading was recorded.

The experiments were performed in air at room temperature and relative humidity from 46% to 55%. When the specimen was heated, it was kept in a constant temperature tank. As it was difficult to guarantee a uniform temperature around the SMP actuator, we raised the temperature to over 70 °C (significantly above T_g of 45 °C) to ensure that all of the SMP material in the actuator was well inside the rubbery state. The internal pressure was measured with a pressure sensor (Keyence Co., AP-43, AP-C40).

5. Results and discussions

5.1. Simple actuation

First, we checked the motion of the newly developed SMP air actuator through the actuation path shown in Fig. 3. The motion of the prototype is shown in Fig. 6. The actuator was initially fixed at the resting length without a load. When the actuator was heated at atmospheric pressure under a constant load of 62 N, it gradually elongated (Fig. 6(a)). The reason is that the area of the SMP in a low modulus state ($T > T_g$) increased. Additionally, the increase in deformation may also include the creep of the SMP. When air at 0.2 MPa was supplied, the actuator contracted (Fig. 6(b)). When the actuator was cooled it remained at the contracted length even when the internal pressure was decreased (Fig. 6(c)). The actuator was kept in this state to check the shape fixity. The length of the fixed actuator with 62 N load and three different actuated lengths are shown in Fig. 7 for a period of 1 h after it cooled to below T_g. This figure shows that the actuator can be fixed at its actuated length. This experiment confirmed that this actuator has the characteristics needed for it to operate under the concept shown in Fig. 3.

We then applied a 0.2 MPa square wave pressure with a frequency of 0.05 Hz while changing the temperature of the actuator under a constant load of 62 N. Namely, we opened or closed the solenoid air valves every 10 s by a timer (0.05 Hz). The motion of the prototype is shown in Fig. 8. When the temperature increased, the deformation induced by the pressure variations increased (Fig. 8(a)). After the actuator was fully heated above T_g, the deformation became constant (Fig. 8(b)). Then, when the temperature decreased, the deformation of the actuator decreased (Fig. 8(c)).

The motion of the actuator under a constant load of 62 N when heated whilst simultaneously applying a constant inner pressure

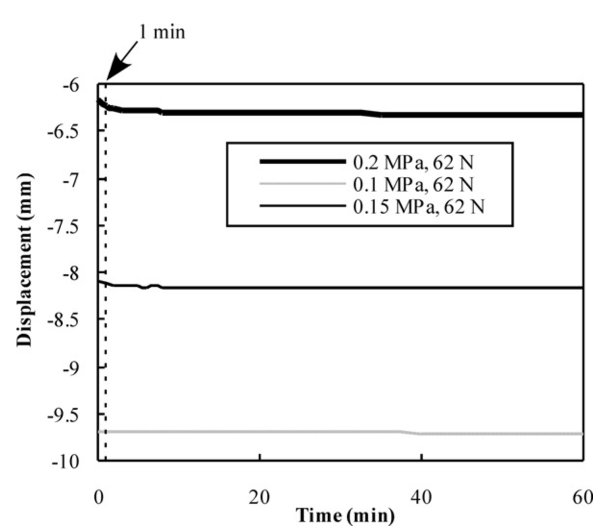

Fig. 7. Transition of shape fixity state of the McKibben artificial muscle that uses SMP ($T < 30$ °C) under a constant load (62 N). At 1 min, the inner pressure of the actuator is reduced to the environmental pressure, as shown in Fig. 6(c).

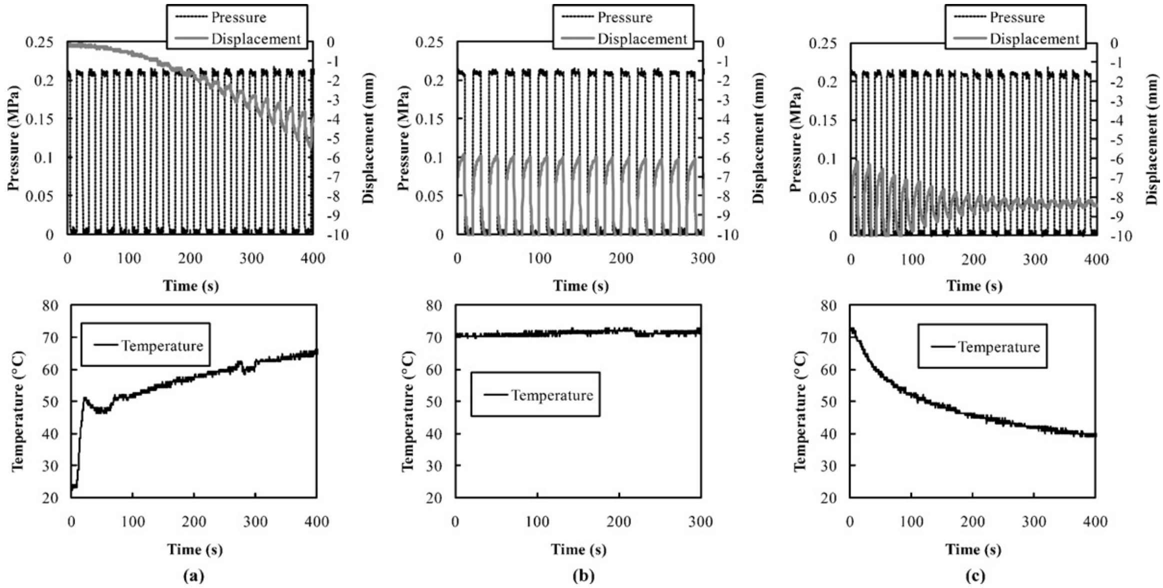

Fig. 8. Motion of the prototype actuator when we applied a 0.2 MPa square wave pressure (0.05 Hz) with heating and cooling under a constant load (62 N). (a) $T < T_g \rightarrow T > T_g$. (b) $T > T_g$. (c) $T > T_g \rightarrow T < T_g$.

of 0.2 MPa is shown in Fig. 9. When $T < T_g$, even though the internal pressure was high, the actuator did not contract because the SMP was in the rigid state. When the actuator was subsequently heated, it contracted. This phenomenon shows that the actuator can be actuated thermally, given a pre-applied pressure.

5.2. Isotonic experiments

The relationship between the internal pressure and displacement of the McKibben actuator with or without SMP when a 0.2 MPa square wave pressure with a frequency of 0.05 Hz was applied under a constant load of 62 N is shown in Fig. 10. Clearly the newly developed actuator shows a smaller displacement. The voids in the braided mesh of the newly developed actuator were filled with SMP, as shown in Fig. 11. The coated SMP is shown as white filling between the black threads of the mesh. Taking this into account we can see that a large displacement of this actuator was prevented because the SMP acted as spring and damper elements.

When a conventional McKibben actuator is shortened, the input energy is partly consumed by the rotational and bending resistances of the thread, swelling resistance of the rubber, and frictional resistance between the thread and rubber. The geometric reorientation of the thread is important for the shortening mechanism of the McKibben actuator [10]. In the case of the SMP air muscle the SMP resin affects this mechanism and constrains actuator contraction.

In this study, the SMP coating was generally thicker than desired, as shown in Fig. 11(a). A close-up view of the other areas of the mesh is shown in Fig. 11(b). In this figure, the voids indicated by the arrow were not completely filled with SMP. Rather, the thread was surface coated only. This smaller amount of coating may be sufficient, if extended over the whole actuator, to produce an effective actuator whist maintaining a good degree of shape fixity.

Additionally, the non-uniformity of the thickness of SMP can be seen in Figs. 5 and 11 (white indicates the presence of small bubbles in the clear resin). In future studies, finer control of the coating thickness will be necessary. Although we coated the SMP outside the mesh, it was difficult to coat the mesh uniformly with a brush. Therefore, it may be more satisfactory to coat the outside of the inner tube before wrapping the inner tube with the braided mesh.

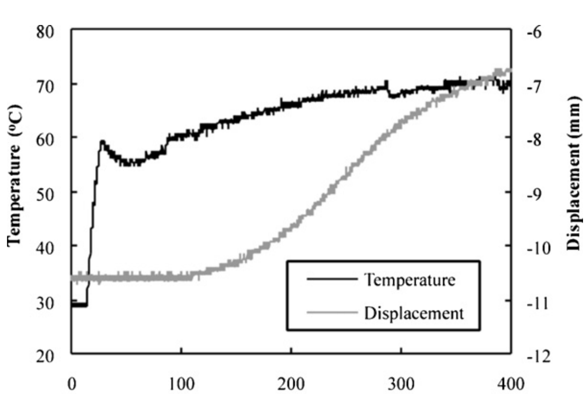

Fig. 9. Motion of the prototype actuator when the actuator with a constant inner pressure (0.2 MPa) was heated under a constant load (62 N).

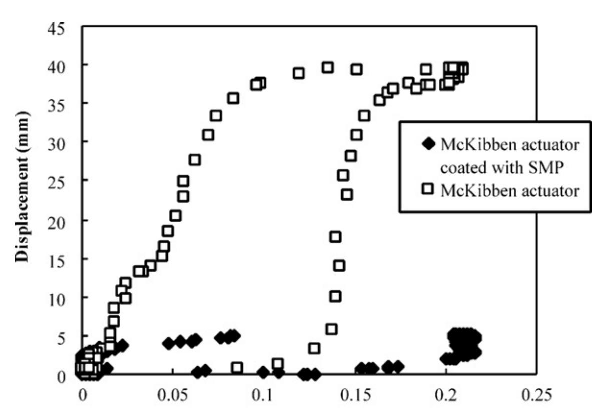

Fig. 10. Relationship between internal pressure and displacement of the prototype under a constant load (62 N). A 0.2 MPa square wave pressure with a frequency of 0.05 Hz was applied.

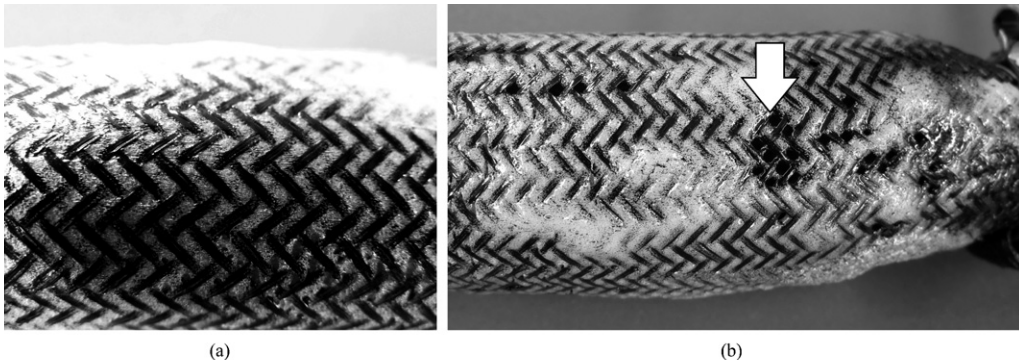

Fig. 11. Close-up view of the prototype. The arrow points to an area not filled with SMP.

5.3. Isometric experiments

These experiments involved measuring the blocked (i.e. zero displacement) force of the McKibben actuator with or without SMP, when the internal pressure was varied, is shown in Figs. 12–13. The pre-extensions of the actuators were 1 cm.

First, we applied a 0.2 MPa square wave pressure with a frequency of 0.05 Hz while changing the temperature of the actuator under a constant length. The generated force of the actuators is shown in Fig. 12. Similar to Fig. 8, the generated force induced by the pressure variations increased according to the raise of the temperature (Figs. 12(a) and (c)). After the actuator was fully heated, the generated force became constant (Fig. 12(b)).

The generated force of the prototype above T_g (internal pressure = 0.2 MPa) is shown in Fig. 13. Note that the air valve was opened at 0.5 s. The generated force of the SMP actuator was larger than the McKibben actuator (Fig. 13). The increase in generated force can be attributed to the deformation resistance of the coated SMP. Under all conditions, the time delay was not large.

It is interesting to compare the proposed SMP-pneumatic actuator with the SMP-dielectric elastomer actuator developed by Pei et al. [22] since both show the fusion of two different actuation mechanisms into a single actuator. Although Pei at al. report high actuation strain and energy density the two actuators are pre-disposed to different applications. For example, McKibben actuators can typically drive larger loads than electroactive polymers. Also in many industrial applications, such as aircraft systems, a compressed air supply is readily available and the emphasis is therefore on weight reduction. Here the McKibben-based actuator is attractive because it can supply large force and/or displacement in a lightweight package. Clearly there is the potential to combine the three principles of dielectric actuation, pneumatic actuation and shape memory effects in an even more sophisticated and versatile actuator.

5.4. Passive deformation

The relationship between the displacement and applied load with 0 MPa pressure is shown in Fig. 14. As shown in this figure, the coating of the SMP increased the deformation resistance. This resistance increased when the SMP changed from the rubbery state to the glassy state. Because the length differs between the glassy and the rubbery states due to thermal expansion of the SMP resin, the two curves in Fig. 15 intersect. Moreover, due to the coating of the SMP, the relationship is nonlinear.

Next the generated strain was measured as the SMP actuator was stretched at a constant rate (5 mm/min) and constant air pressure to a load of 49 N or a displacement of 50 mm where it was maintained for over 15 min. The results of these experiments are shown in Fig. 15 and can be compared to the results for a McKibben actuator in Fig. 16. It is clear that the SMP coating increased

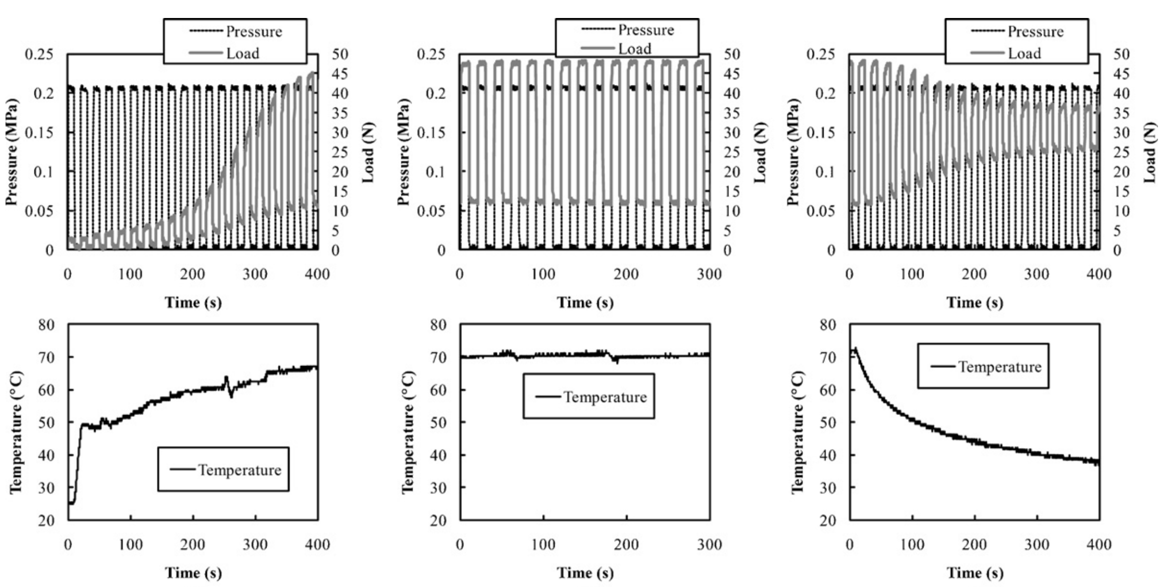

Fig. 12. Generated force of the prototype actuator when we applied a 0.2 MPa square wave pressure (0.05 Hz) with heating and cooling under a constant length (initial displacement = 1 cm). (a) $T < T_g \rightarrow T > T_g$. (b) $T > T_g$. (c) $T > T_g \rightarrow T < T_g$.

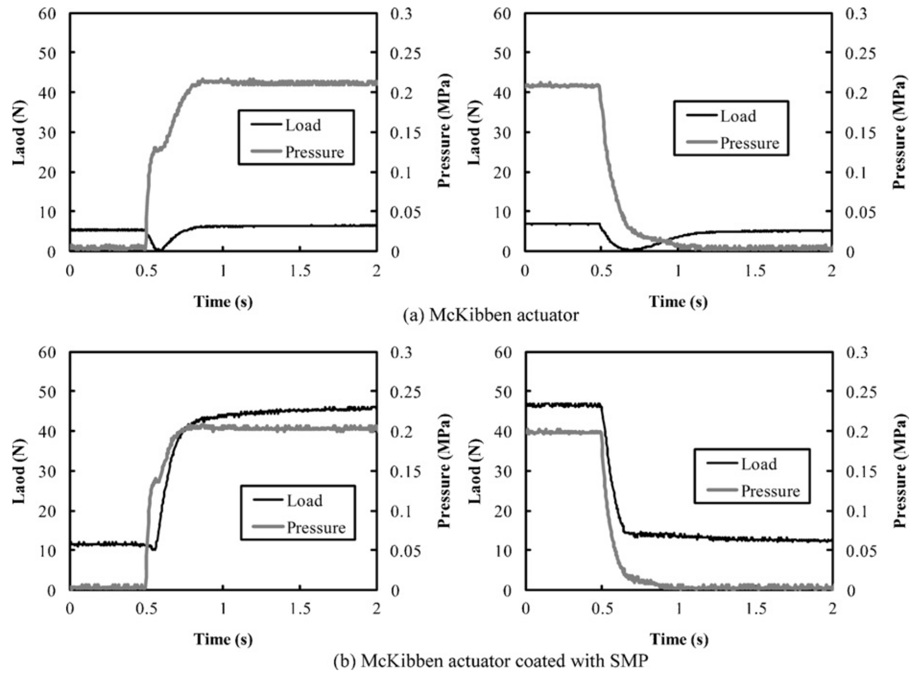

Fig. 13. Generated force of the prototype under a constant length (initial displacement = 1 cm; maximum internal pressure = 0.2 MPa).

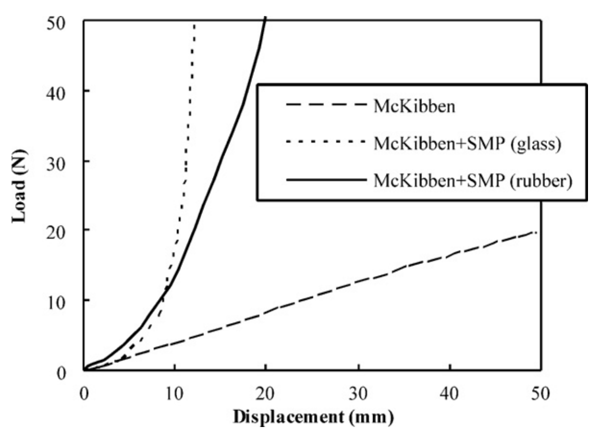

Fig. 14. Passive tension–length relationship of the prototype under a constant pressure (0 MPa).

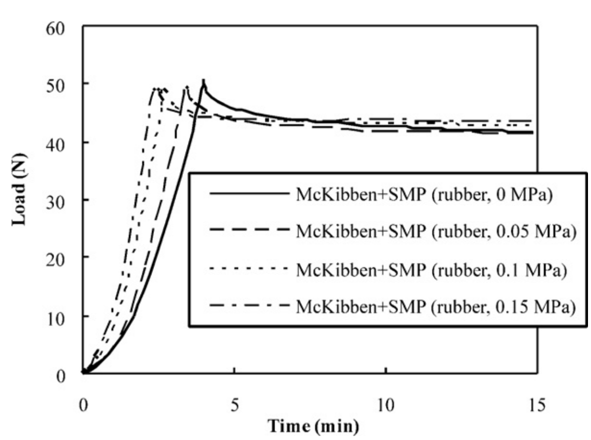

Fig. 15. Passive tension–length relationship of the prototype under a constant pressure. Internal pressure was changed for each experiment (0–0.15 MPa). The specimen was heated above 73 °C.

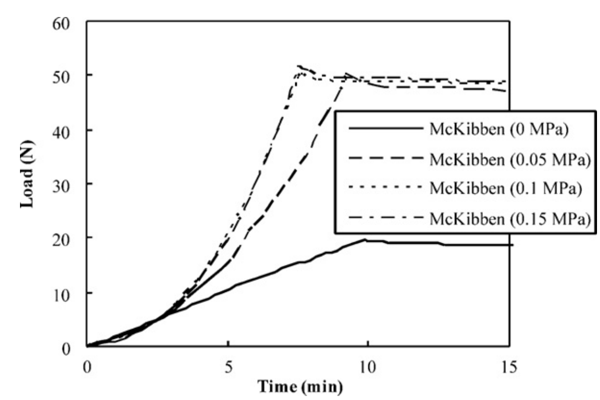

Fig. 16. Passive tension–length relationship of the commercial McKibben artificial muscle under a constant pressure. Internal pressure was changed for each experiment (0–0.15 MPa). The specimen was heated above 73 °C.

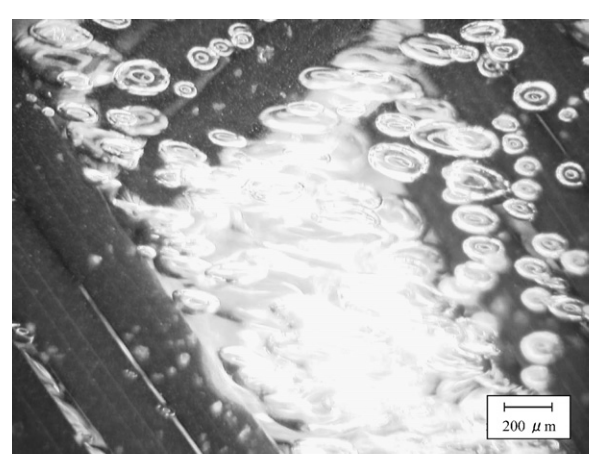

Fig. 17. Close-up view of the prototype. Many bubbles are seen in the SMP.

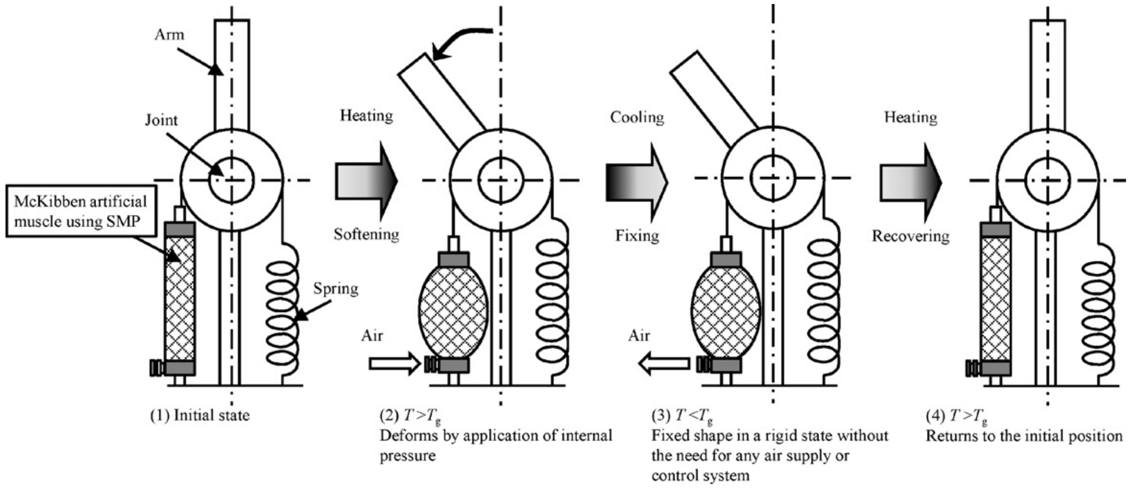

Fig. 18. Motion principle of the McKibben artificial muscle that uses SMP in the robotic arm application.

the stress relaxation of the actuator. It can also be seen that when the internal pressure increased the deformation resistance also increased, although this relationship is nonlinear. These results show that when this actuator is considered as a passive element its stiffness can be varied not only by varying the inner pressure, but also by varying the temperature. Besides that, although the change in the elastic modulus between the glassy and rubbery states of the SMP used in this study is 300 times as shown in Table 1, the stiffness change of the proposed actuator can be larger by varying the inner pressure.

The nonlinear deformation properties of the new actuator can be attributed to the nonlinearity of the SMP material itself. Furthermore, because of the complex sheer and stretch deformations that each of the voids in the mesh undergoes, the nonlinearity of the actuator is further increased. Namely, the SMP is not only stretched, but also bent. As shown in Fig. 17, the bubbles in the SMP may also contribute to the nonlinear deformation properties. But, this non-linear deformation property is not disadvantage from the viewpoint of its shape fixity because the actuator can be fixed at arbitrary position by cooling.

From the viewpoint of a passive element, there are several problems. For example, if the number of actuators is increased, it would become possible for the arm to support more load. On the other hand, the resistive force also becomes large when the actuators are actuated. Moreover, when space is limited, it may be impossible to attach more actuators. Although the proposed actuator can support large loads when in the fixed state the actuation strain is less than the conventional McKibben actuator as shown in Fig. 10. This naturally leads to future work on further specification and characterization of the SMP-McKibben actuator, for example with respect to bandwidth and cyclic lifetime.

6. Robotic arm application

In future studies, we will apply the SMP air muscle to a robotic arm. The operating principle of the robotic arm is illustrated in Fig. 18. The air muscle provides a contractile force and therefore a counteracting spring is necessary to ensure bi-directional motion. Note that the arm can be held rigid with respect to loading in one direction only. Namely, the arm is supported by the SMP in one direction, and is supported by the spring in the opposing direction. Although two SMP actuators are needed if the load must be supported in two directions, it should be noted that many robotic arms support a load against gravity, and hence would need rigid fixing in one direction only.

Moreover, as the pneumatic actuators require a pneumatic pressure source that is bulky and noisy, the total system may become large. Besides that, our proposed actuators require a heat source. Therefore, in order to utilize this technology on a mobile robot it will be necessary to miniaturize the whole system including the pneumatic pressure source and the heat source. Also for the miniaturization of the pneumatic pressure source, it will be necessary to economize and optimize pneumatic valve control. On the other hand, as T_g of many SMPs is close to room temperature, it may be possible to utilize ambient or waste heat without the addition of a large dedicated heat source.

We will investigate the performance of SMP air muscles where thermal energy is provided by a variety of sources including light illumination, electric current, or a hot saline solution [16,18]. Clearly a narrow transition temperature range for full transformation from the glassy to the rubbery states reduces the heat consumption of the device [12], but a wider temperature transition range may enable a gradual stiffness change. This variable stiffness property is extremely attractive for robotic applications. Moreover, a wide temperature transition range may enable not only dual but also triple, and higher, memory effects [23].

7. Conclusions

In this study, we have presented a new air muscle based on the enhancement of a McKibben actuator with shape memory polymers. We coated the braided mesh shell of a commercial McKibben artificial muscle with SMP resin and fabricated a prototype of this actuator. The experimental results of a preliminary investigation confirm the feasibility of the proposed actuator to transform between a deformable air muscle and a rigid structure. In this way we have shown how enhanced properties of variable stiffness and shape fixity have been introduced into this actuator. Applications of this technology include actuators for engineering, robotics, medicine and human–machine interaction.

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Biographies

Kazuto Takashima received his BS and MS degrees in mechanical engineering from Kyoto University in 1997 and 1999, respectively. He worked at Matsushita Electric Industrial Co., Ltd. from 1999 to 2003. He received his PhD from the Faculty of Engineering, Kyoto University, in 2006. He was a research scientist at RIKEN from 2006 to 2010. He moved to Kyushu Institute of Technology as an associate professor of Graduate School of Life Science and Systems Engineering in 2010. His research interests are medical sensors, robots, surgical simulation systems, and artificial muscle.

Dr Jonathan Rossiter is a senior lecturer at Bristol University and head of the Soft Robotics research group at Bristol Robotics Laboratory. His research interests include biomimetic soft robotics, soft actuator technologies, electroactive polymers, human-like tactile sensing and synthetic biology.

Toshiharu Mukai received his Doctor of Engineering degree from the University of Tokyo, Japan, in 1995. He was a frontier research scientist at RIKEN from 1995 to 2000, after which he pursued a postdoctoral fellowship (2000–2001) at the Laboratoire de Neurobiologie in France. From 2001 to 2008, he headed the Biologically Integrative Sensors Laboratory at RIKEN's Bio-mimetic Control Research Center. Since 2007, he has headed the Robot Sensor Systems Research Team at RIKEN-TRI Collaboration Center for Human-Interactive Robot Research. His current research interests include sensor fusion, active sensing, shape recovery from image sequences, neural networks, and artificial muscle.