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An Assessment of the Body Joint Bending Actuator using a Shape Memory Alloy

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Abstract: To strengthen limbs which are injured in an accident, a traditional rehabilitation device has been adopted. However, it is heavy and complex, a light-weight body joint bending actuator which is made of a Shape Memory Alloy (SMA) and is simpler than traditional rehabilitation devices is therefore proposed. Here, an SMA-made actuator can offer the resistance needed for a rehabilitation program. A Ti-Ni based SMA is adopted for the body joint bending actuator. To facilitate the swinging angle and the related bending torque, various structures of the SMA-made body joint bending actuators (a one-bunch SMA actuator and a six-bunch SMA actuator) have been adjusted in the experimental work by varying the number of SMA fibers in a bounded bunch. Results reveal that the structure-A (a six-bunch SMA fiber with 8 fibers per bunch) and the structure-B (a one-bunch SMA actuator with 50 fibers per bunch) have similar functions- the bending angle is 158° and the maximum bending torque is 0.155 Nm. Moreover, depending on the patient's condition, both the maximum swinging angle and the velocity are adjustable by the patient via the PC-based control system. In addition, to avoid damage to the actuator, a maximum operating temperature of 90°C is preset on the SMA.

Key words: Smart material, temperature, therapy, assistive devices of rehabilitation, PC-based

INTRODUCTION

The joint which dominates motion in a body is often injured in an accident. Therefore, a therapeutic technique for the injured joint is essential. Medical treatment for joints includes surgical operations, inplasters, hot packs and cold packs. However, a comprehensive process is needed for complete rehabilitation. Without rehabilitation, a joint will ache, a muscle will shrink and a joint will cease to function. Two kinds of joint rehabilitation are used: one is active physical therapy in which the patients swing their limbs, the other is passive rehabilitation in which the limb is manipulated using Continuous Passive Motion (CPM). Currently, Continuous Passive Motion (CPM) adopts a traditional mechanism such as a worm gear, gear and linkage which are driven by a motor and a hydraulic or a pneumatic power unit (Saito *et al.*, 2005). However, because of its heavy bulk and a complicated operating procedure, the rehabilitation device is inconvenient. For example, a rehabilitation device with a traditional mechanism used for an upper limb is huge and heavy and needs to be operated at a fixed location (Huang *et al.*, 2001). Furthermore, only one upper limb can be used with this rehabilitation device. For a rehabilitation device used on a lower limb, the patient will not only have to lay on a bed but also will have to use an assisting device (Wu *et al.*, 2007). Obviously, the numerous inconveniences such as a complicated operating process, inflexible force adjustment, machine maintenance and higher cost result in slow sales and infrequent usage. To overcome these drawbacks, a new body joint bending actuator driven by the SMA was developed. The SMA-made actuator is compact and flexible in adjusting the rehabilitation force by varying the number of SMA fibers. Moreover, depending on the patient's condition, both the maximum swinging angle and the velocity are adjustable by the patient via the PC-based control system. In addition, to avoid damage to the actuator, a maximum operating temperature of 90°C on the SMA is preset and monitored.

SHAPE MEMORY ALLOY

The SMA, one kind of smart material, memorizes an original shape by using the phase transformation (Addington and Schodek, 2004). The shape of the SMA can be recovered via the transformation of the crystal structure from the Austensite (at a lower temperature) to Martensite (at a higher temperature) by heating up the SMA to a critical temperature (As) at which time the crystals of the Austensite start to grow (Wang, 2004). Three kinds of primary SMAs include the Ti-Ni, Cu and Fe

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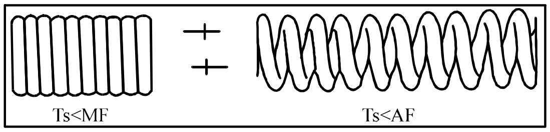

Fig. 1: Deformation of a bidirectional shape memory alloy under a heating and cooling process

series. According to the metal's characteristics, the SMA divides into (1) memory effect material and(2) pseudo-elastic material. A bidirectional shape memory alloy indicated in Fig. 1 will be stretched when it is heated to the Af and above. However, the coiled spring will shrink to the original length when it is cooled to Mf and below. Moreover, the spring will stretch when it is heated again.

EXPERIMENTAL SET UP

SMA-made bending actuator: A bidirectional shape memory alloy ($Ti_{50}Ni_{50}$) that is 0.15 mm in diameter is adopted in the experimental work. First, a SMA with one fiber is adopted as the bending actuator. As shown in Fig. 2, a testing mechanism in converting the SMA's contraction force into a rotation motion is established. Obviously, the length of the mechanism is closely related to the length of the SMA's fiber. Moreover, the output swinging angle and torque will depend on the radius of the rotating axis. An SMA for a rotating axis 100 mm in length with a radius of 8 mm has been preset. As shown in Fig. 3, the rotating axis will rotate counter-clockwise when the SMA is heated. On the other hand, when the heating process stops, the rotating axis will rotate clockwise because of the SMA and the rubber band recovery forces.

Second, one end of the SMA is fixed at the axis of the primary driver. The other end is put onto a moveable slider in which the tension of the SMA can be adjusted. As shown in Fig. 4, to reach a sufficient torque, a six-bunch SMA fiber (φ 0.15 mm) with 8 fibers per bunch is adopted. As shown in Fig. 5, two gears used for the force transfer are utilized with a mold 1. To avoid damaging the gears, the ratio of the gear teeth (80 teeth and 20 teeth) is four to one. As shown in Fig. 6, a distorted screw spring is fixed onto the output axis. Moreover, the driving axis will connect with the limb's board. The primary driver will be actuated with a swinging angle when the SMA is heated. The output axis will produce four times the swinging angle. Moreover, the limb board connected with the output axis will be actuated. Subsequently, a reversed motion driven by the recovery force from the SMA and the distorted screw

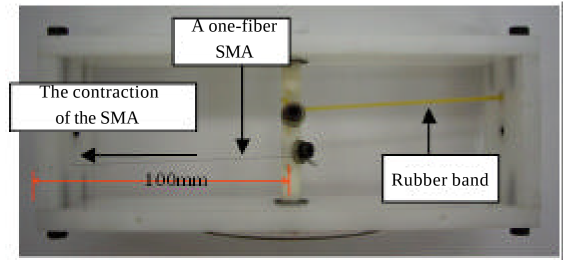

Fig. 2: A SMA with one fiber

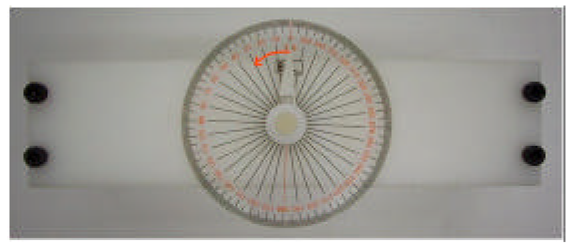

Fig. 3: The rotating axis rotating counter-clockwise when the SMA is heated

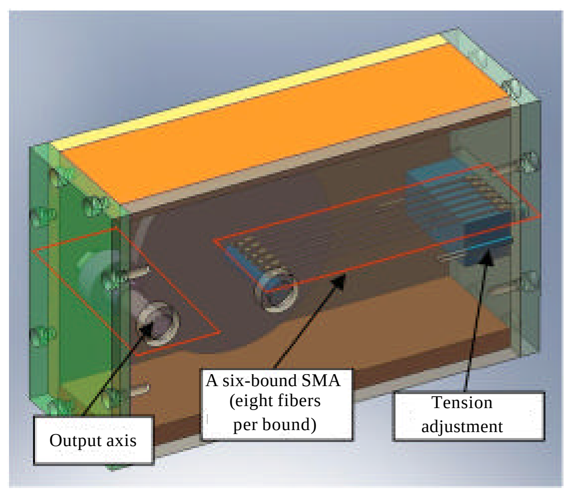

Fig. 4: Design of a bending actuator using a six-bunch SMA (8 fibers per bunch)

spring will be performed when the heating process on the SMA stops. Here, to provide an auxiliary bending force for the right arm, the bending actuator is placed outside the arm.

In order to be manipulated easily, depending on the patient's condition, the bounds of SMA in the bending actuator can be adjusted up to six. The number of SMA fibers per one bound is also adjustable. The preset figure

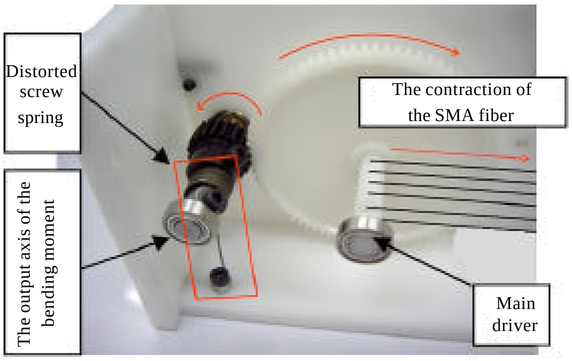

Fig. 5: A two-gear force transferring system (mold = 1; teeth ratio = 4)

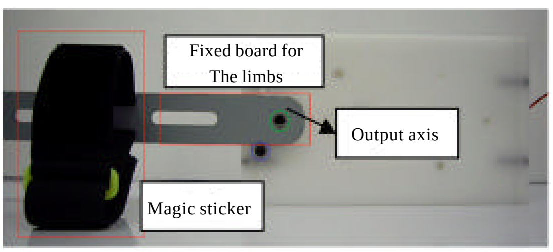

Fig. 6: A distorted screw spring fixed onto the output axis

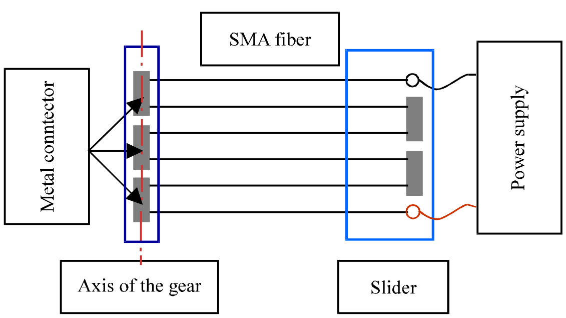

Fig. 7: Mechanism of a beaming actuator with six bounds in parallel

number is eight fibers per bound. To distribute the heating flux, the fibers shall be screwed together during the heating process.

The main purpose for the bending actuator is to provide an assisting force for the joint's contraction. The SMA can also be fixed on the other end to actuate the gear in a reversed motion if the resistant force for the joint's contraction is required. One terminal fixed on the slider can provide eight SMA fibers (φ = 0.15 mm) per bound. As shown in Fig. 7, six bounds in parallel are used in the mechanism. To shorten the volume of the bending actuator, fifty SMA fibers are put in one bound. To appreciate the performance of the output torque and swinging angle, a series of experimental testing shown in Fig. 8 is processed. As shown in Fig. 8, the distance between the gravity points of the lower-limb board and the output axis is 105 mm. To evaluate the maximal output torque with respect to a six-bound (eight fibers per bound) bending actuator and a one-bound (fifty fibers per bound) bending actuator, a counterweight has been added to the lower-limb board.

A PC-based temperature controlling system: For the safety purposes, a PC-based control system (Tse and Chan, 2003; Mustafa *et al*., 2007) using a VB interface is established. As shown in Fig. 9, the SMA's temperature

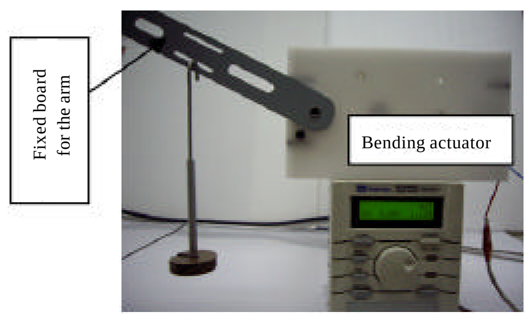

Fig. 8: The outline of the lower-limb board and the output axis

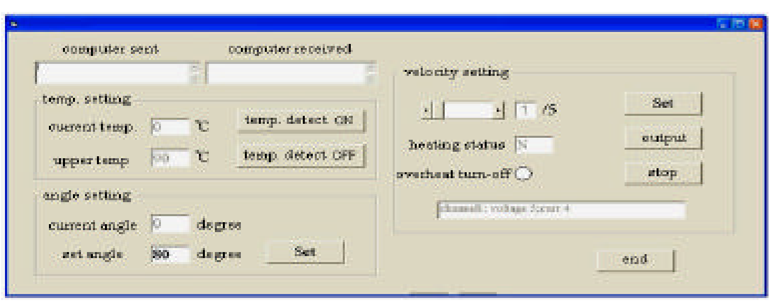

Fig. 9: The VB interface of a PC-based system

will be detected via the RS232 in conjunction with the VB interface. The electrical power will be turned off when the temperature exceeds the upper limit. Moreover, both the angular velocity and the swinging angle of the bending actuator can be set via the PIC18F452 controller by feeding back the angle value from the A/D device.

RESULTS AND DISCUSSION

The experimental data for a device composed of a single SMA's fiber is shown in Table 1. As indicated in Table 1, the maximal output angle is 62°. It has been seen that the retained angle will move away from 0° after being cooled if the electrical power heating the SMA is rising. However, the maximal output angle will not change. Because of the fixed value of resistance in the electric circuit, the electrical power in the SMA will increase when the voltage become higher; thereafter, the response in the SMA's deformation and the angular velocity in output will quicken. Consequently, to avoid overheating, the heating process for the SMA will be monitored via the temperature detecting and feedback system.

The experimental data for a device composed of a six-bound (eight fibers per bound) SMA is shown in Table 2. As shown in Table 2, the angular velocity is proportional to the electrical power. Similarly, the retained angle will increase if the manipulated temperature on the SMA increases. Moreover, the output swinging angle reaches 158° using a gear tooth ratio (4).

The experimental data for a device composed of a one-bound (fifty fibers per bound) SMA is shown in Table 3. Similarly, the angular velocity and the retained angle are closely related to the electrical power and the heating temperature. As can be seen in Table 2 and 3, because of the accumulation effect of the one-bound (fifty fibers per bound) SMA, its angular velocity is faster than that of the six-bound (eight fibers per bound) SMA.

In reviewing the earlier research works in the rehabilitation field, Park *et al.* (2008) adopted a portable motor-driven rehabilitation device in conjunction with a remote manipulation system; however, the time-lag which may delay the rehabilitation process occurred; moreover, both of the rehabilitation's force and the operating time are not adjustable. Kiguchi *et al.* (2003) used a traditional actuator (DC motor) as a driver used in the rehabilitation process; however, the rehabilitation device is heavy, complex and noisy. Sasaki and Noritsugu (2009) provide a pair of rehabilitation devices (master and slave). The slave part will be trained by the master part. Air compressed with pressure provides the power source. However, the rehabilitation is complex. Miyaguchi *et al.* (2007) adopted DC motor as an actuator in the rehabilitation; however, it is heavy in bulk and noisy in operation. De Laurentis *et al.* (2002) adopted a bundle of SMA fibers as an actuator. It can provide a higher output force (48.45 N). However, the output force used in a rehabilitation device is still insufficient. Shiraishi *et al.* (2008) applied SMA fiber in the shrink motion for artificial heart design only. Yang and Lin (2007) used SMA fiber as muscle actuator only.

Table 1: The experimental data of the bending angles for the bending drive mechanism using a single-fiber SMA

Electrical voltage (V)	Electrical circuit (A)	Maximum angle	Time (sec)	The retained angle when the electrical is power off
3	0.42	58°	2	7°
4	0.56	62°	0.2	8°
5	0.68	62°	too fast	9°
6	0.77	62°	too fast	10°
7	0.99	62°	too fast	12°

Table 2: The experimental data of the bending angles for the bending drive mechanism using six sets of SMA (eight fibers per bound)

Electrical voltage (V)	Electrical circuit (A)	Maximum angle	Temperature (°C)	Time (sec)	The retained angle when the electrical is power off
3	0.64	25°	43.1	37	2°
4	1.01	145°	61.0	34	6°
5	1.34	154°	70.8	14	8°
6	1.56	154°	70.0	8	9°

Table 3: The experimental data of the bending angles for the bending drive mechanism using a set of SMA (fifty fibers per bound)

Electrical voltage (V)	Electrical circuit (A)	Maximum angle	Temperature (°C)	Time (sec)	The retained angle when the electrical is power off
0.77	3	120°	75.0	90	12°
1.06	4	120°	70.5	20	13°
1.27	5	122°	71.6	14	14°
1.49	6	132°	69.0	8	14°

To overcome the drawbacks mentioned above, a study of a bidirectional shape memory alloy ($Ti_{50}Ni_{50}$) used in a body joint bending actuator is developed. As has been seen in the experimental study, the required rehabilitation force was obtained by pulling the right arms of four people who weighted around 70 kg. Results reveal that the required bending moment for a man is 3.19 Nm. Experimental results also reveal that the output torque for a device composed of a six-bound (eight fibers per bound) is 0.147 Nm. Moreover, the output torque for a device composed of a one-bound (fifty fibers per bound) is 0.158Nm. It has been seen that the rehabilitation performance between these two mechanisms, a six-bound with eight fibers per bound and a one-bound with fifty fibers per bound, are similar.

To reach the targeted torque of 3.19 Nm, an improvement of the SMA's mechanism using a 20 bound (fifty fibers per bound) SMA is required. However, the volume of the SMA's mechanism will increase; therefore, a study of new mechanisms for amplifying the output torque in future is necessary.

CONCLUSIONS

A bidirectional shape memory alloy ($Ti_{50}Ni_{50}$) that is 0.15 mm in diameter is adopted as a body joint bending actuator. As has been seen in the experimental study, the rehabilitation performance between two kinds of mechanisms (structure-A: six-bound with eight fibers per bound; structure-B: one-bound with fifty fibers per bound) are similar. However, the volume of the structure-B is more compact than that of the structure-A. Experimental results reveal that structure-B will provide a maximal swinging angle of 158° and have a maximal output torque of 0.158 Nm.

Consequently, to avoid damage to the actuator, a maximum operating temperature of 90°C on the SMA has been preset. Moreover, the body joint bending actuator can be adjusted to fit the patient by adjusting the swinging angle via a VB interface of a PC-based control system.

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