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Force Model Study for the Bending Actuator with Multiple Shape Memory Alloy Wires

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***Abstract*—This research aims to create the cantilever bending actuator with multiple wires of the $Ti_{50}Ni_{45}Cu_5$ Shape Memory Alloy (SMA) that is a unidirectional deformation of material using as 1.0mm in φ and 0.12m in length. The mathematical model of an SMA-made actuated force has been established via experimental work. The SMA effect is based on the phase transformation form Martensite to Austensite which not only produced in shape recovery but will also increase the stiffness of the alloy when the SMA is heated. The modules of elasticity, a function of temperature, will be established via experimental data using multiple SMA wires with five kinds of wire arrangements. To reach the state of a Pseudo-Elastic state, the operational temperature over Af in Austensite is set at 71 ℃ and above. The equivalent elastic coefficient (E) will be acquired by plugging the data of various loading and related deflections into the theoretical defection formula. Subsequently, the experimental data with respect to loading for multiple-wire actuator will be built up using a regression process in conjunction.**

Finally, the results reveal that the bending force for a multiple wire and SMA-made cantilevered actuator is linearly proportional to the number of wires. Consequently, the bench-bar type actuator is superior to the other actuators. However, the quadrel type SMA-made actuator's bending force does not perform well. And, the performance of spool type SMA-made actuator's bending force with bound and distorted wires is even worse.

***Index Terms*—Shape Memory Alloy (SMA), cantilever-beam actuator, shape memory effect, fixed type, pseudo-elastic state**

I. INTRODUCTION

IN the past several decades, various actuators used in biomedical engineering such as the micro actuator, linkage, and thermal switch have been developed. Kode *et al.* developed a micro mechanical fixture used to deal with external wounds [1]. The tendon type fixture can be operated at a 45 degree angle using a linkage actuated by electrical power. The fixture provides a clamping force of about 8 (N) by heating the SMA [2]. Komatsubrar *et al.* proposed a new actuator moving in a micro conduit. A spring, a TiNi-made SMA of eight-wires (0.35 mm in φ and 0.06 m in length), has been adopted to actuate the actuator using a heating process on the SMA [3].

Velazquez *et al.* proposed a TiNi-made SMA spring used to enhance the clicking on a platform. The SMA-made spring (0.7 mm in φ and 0.0635 m in length) provides a contraction force with around 12 (N). This array-type SMA can provide more output force and tactile feeling [4]. In 2006, Rossiter *et al.* developed a new actuator that served as an artificial muscle. The actuator was made of an ionic-polymer metal Composite (IPMC). The motion of the actuator was like a moving fish swinging back and forth and was slow and non-repeatable [5]. Also, in 2006, Huynh *et al.* demonstrated the actuator is made by an electric-conductive polymer material. Using 1 volt, the actuator, providing 0.5 (mN), was applied as a fixture force for a cantilever beam [6].

Alici *et al.* proposed a new actuator which was made of a combined electric-conductive polypyrrol (PPY) material. With the verification of both the finite element method (FEM) and the experimental work, the actuated force caused by the bending angle of a bending actuator can be predicted. Both the strain and bending angle will reach 0.35 and 14.3 degrees when the electrical power is 1 volt [7]. An air-compressed artificial muscle was proposed by Camerillo *et al.* in 2006. On the basis of a force modulus, a compressed type tendon-driven robot can be used in a linear control system. The bending and axis motion of the robot will be predicable [8]. In 2009, Ho and Desai proposed a micro-type multi-joint actuator used in a nuclear magnetic resonance (NMR) machine [9]. The range of bending for a nine-joint actuator was ± 30℃ with an error of 2℃ using a temperature feedback control system. The study indicated that an active control with a cooling process is essential in system. In 2006, Gangbin *et al.* proposed a combined cantilever beam embedded with a TiNi-made SMA. Real-time control will be carried out via the combination of Matlab / Simulink and DSPACE. In order to obtain a precise position and reach a higher output force, a feedback control for the electrical circuit and temperature resulting in an 8% deformation of the SMA is required [10]. Based on the cantilever beam model, Hu [11], Wang [12], and Lin [13] established the relationship between loading and deflection when the operating temperature was less than Af. Moreover, the mathematical expression of the linear and non-linear temperature effect with respect to the elastic modulus (E) was established via the experimental data.

To access a higher output force of an actuator, a cantilever-type bending actuator is proposed using a new multiple-wire SMA (1.0 mm in φ and 0.12 m in length) made of $Ti_{50}Ni_{45}Cu_5$. The modules of elasticity, a function of the temperature [14], were

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acquired to establish the mathematical modulus of a bending actuated force via the experimental data. Three kinds of wire arrangements — first, the line type; second, the square matrix type; and the third, the twisted and bounded type — are proposed. Related output forces will be obtained. The mathematical formula for loading with respect to deflection of a multiple-wire actuator will be built up using a regression process in conjunction with the experimental data.

II. MULTI-WIRE SMA-MADE BENDING

A $Ti_{50}Ni_{45}Cu_5$ (1.0 mm in φ and 0.12 m in length) is adopted in the SMA-made Actuator. As indicated in Fig. 1, five kinds of arrangements for the SMA wires (1L: the alone bar type; 2L: the parallel bar type; 4B: the bench bar type; 4Q: the quadrel bar type; 4S: the spool bar type) are proposed. For the alone bar type actuator, as indicated in Fig. 1, one side of the wire is fixed by the Teflon sets. The other side is connected with an electrical circuit that triggers the SMA-made actuator using a heating process.

For the parallel bar type actuator, two SMA wires are parallel. One end of the parallel bar is fixed by the Teflon set. At the other end, two wires are connected with an electrical circuit. Similarly, the bench bar is made of two pairs of parallel bars. One end of the bench bar is fixed by the Teflon set. At the other end, two pairs of wires are connected with an electrical circuit for the purpose of SMA-heating.

For the quadrel bar type actuator, in order to avoid the dislocation of four wires during the end-fixing process, four wires are bound and embedded in a silica tube (2mm for the inside diameter and 4mm for the outside diameter) in advance. The clips are used to fix two ends of the quadrel bar. Moreover, the silica tube can prevent the irregular buckling of the quadrel bar and also isolate the heat transfer from inside the SMA's wires to the outside.

For the spool bar type actuator, four SMA's wires are twisted and bound together. Similarly, the spool bar with twisted and bound wires is embedded in a silica tube. Two ends of the spool bar are fixed by clips.

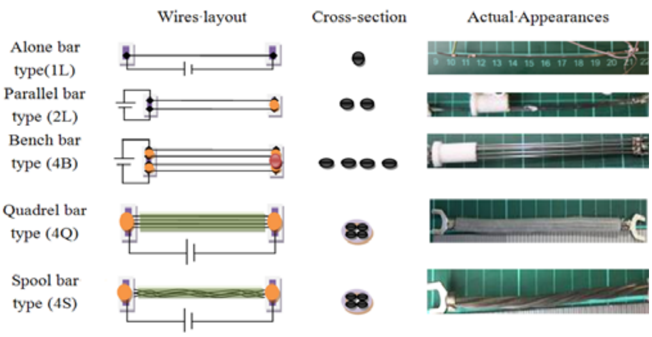

Fig. 1. Five kinds of multi-wire SMA-made bending actuators.

III. EXPERIMENTAL SET UP

In this paper, an equivalent module of elasticity (E) will be obtained by using the theoretical deflection formula of a clamped cantilever in conjunction with experimental deflection data at various loading and SMA arrangements. The heating of the SMA's wire is manipulated by an electrical device via a thermal feedback controlling system. The feedback thermal data is acquired by connecting, with equal span, the thermal couples at the SMA's wire. First, to verify the reliability for the relationship of E, loading, and deflection after enlarging the length of the SMA studied in earlier research [11], the operating temperature is a repeated set at Af at 65℃ or below.

Additionally, the operating temperature is controlled at around Af at 71.1℃ and above. A series of experimental data will be acquired to establish the mathematical model of the driven force. The characteristic properties of the SMA are shown in Table 1.

A. A SMA-made Cantilever Beam System

In order to avoid any influence from environmental temperatures, the SMA-made cantilever beam system will be manipulated in an enclosed box. As shown in Fig. 2, the available space for the box is 0.32 m in width, 0.32 m in height, and 0.28 m in length. To prevent heat loss, the box, made of a polystyrene material 0.020 m in thickness, is equipped with a web camera and a ruler.

Two anti-heat wires penetrate through the box via two holes (one, an upper hole used to pull the actuator back to its original position by using a wire; the other, a lower hole used to add more counterweight through another wire). In addition, the allocation of electrical power will depend on the type of SMA arrangement. As shown in Fig. 3, the thermocouple wires are placed at the front, the middle, and the rear points along the SMA-made cantilever beam. A thermal control system is shown in Fig. 4, the thermal data detected by three wires of thermal couples attached to the SMA's wire will be acquired via a thermal meter (TECPEL317&318) and a DC power supply (PSH-2018).

The experimental temperature is controlled within 70～72°C. The electrical circuit will be turned down when the operating temperature exceeds 72°C. Also, the electrical circuit will be turned up when the operating temperature is lower than 72°C. The experimental procedure is shown in Fig. 5. As indicated in Fig. 5, the operating temperature will be controlled within 71℃±1℃. The image of the deflected cantilever beam will be pictured at various loadings. The experimental work for an every loading will be performed five times. A final value will be obtained by averaging the related data.

B. Calculation for the Deflected Angle and Elastic Module

A web camera with eight million pixels is used to acquire the image of the SMA-made bending actuator via a dialogue programmed in VB language. Thereafter,the bending angle (θ) in Fig. 6 will be automatically calculated by clicking nodes A, B, and C. The deflection will be calculated by plugging θ into trigonometric functions. Consequently, the related elastic modulus (E) will be calculated using the theoretical deflection formula of a clamped cantilever.

Five kinds of SMA-arrangements shown in Fig. 1 are applied in the experimental work. The experimental steps are listed below:

Two kinds of operating temperatures (an Af of 65℃ and 71℃) are adopted.

1) The deflection of the cantilever beam is obtained from the bending angle (θ) using a trigonometric function.
2) Displacement (δ) is obtained.
3) The elastic modulus (E) is calculated.
4) The maximal torque (M) is calculated using M=P*L

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TABLE I
CHARACTERISTIC PROPERTIES FOR THE SMA

As (the starting transformation temperature for Austensite)	315K(42℃)
Af (the ending transformation temperature for Austensite)	340K(67℃)
Ms (the starting transformation temperature for Martensite)	320K(47℃)
Mf (the ending transformation temperature for Martensite)	293K(20℃)
Hysteresis	18(K)
Maximum deformation rate(γ)	6(%)
Heat expansion coefficient(α)	10e3K
Density(D)	6650Kg/m^3

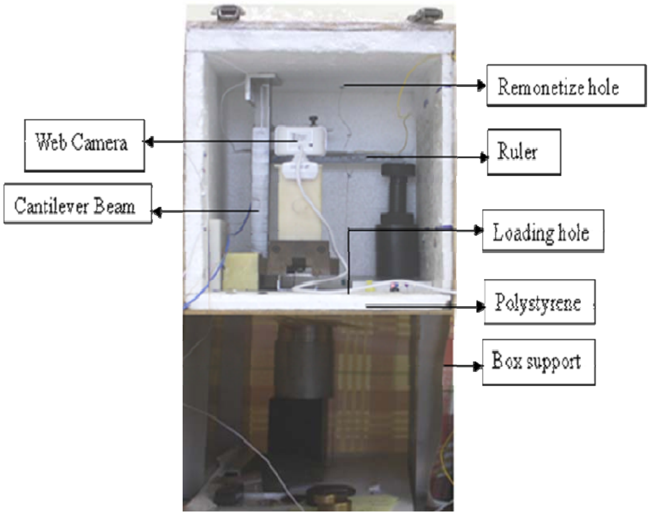

Fig. 2. An experimental box enclosed with polystyrene material.

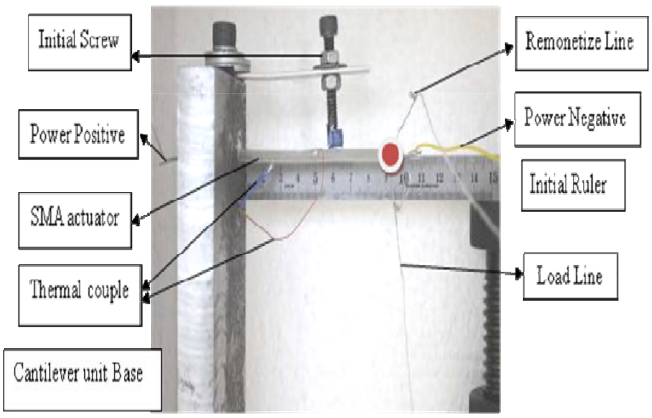

Fig.3. The allocation of thermocouple wires, electrical power, a turn back line, and a loading line.

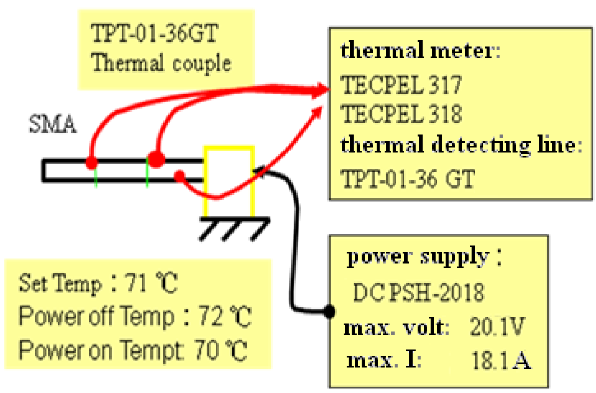

Fig. 4. Thermal control system.

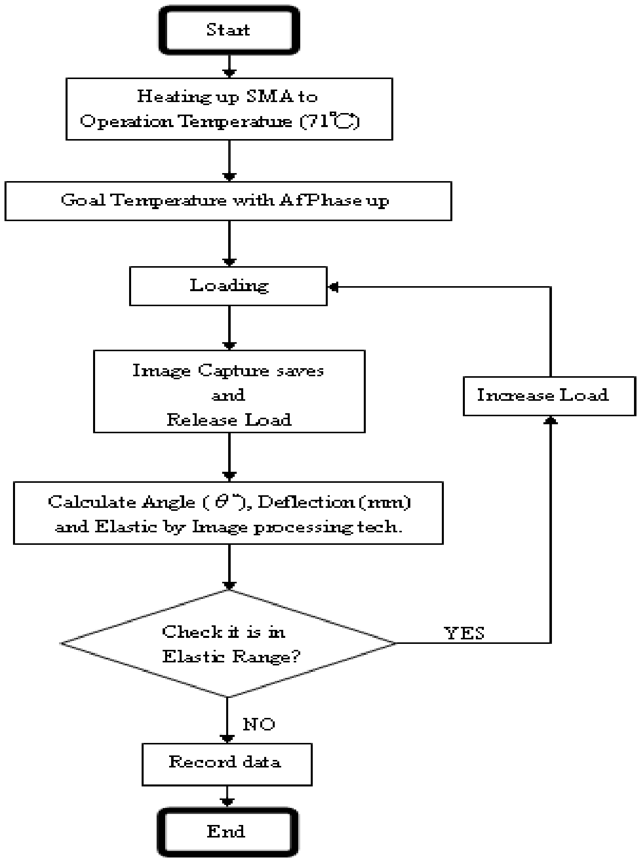

Fig. 5. The experimental procedure.

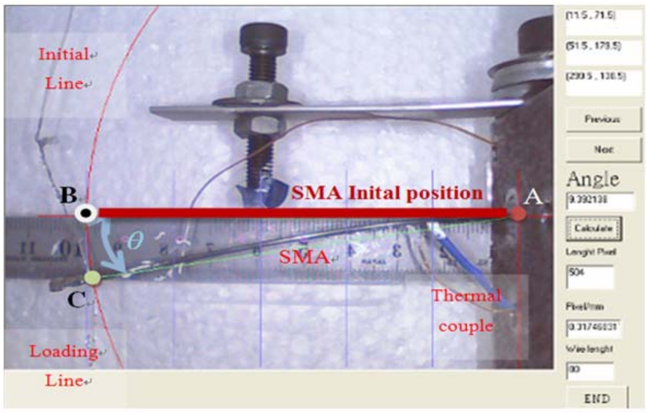

Fig. 6 . A web camera's vision-capturing system used to acquire the image of the SMA-made bending actuator via a VB's dialogue.

IV. RESULTS AND DISCUSSION

A. *Results*

The force model for a multi-wire SMA-made cantilever beam is shown in Fig. 7. The related bending angle (θ) and displacement (δ) can be obtained by varying the loading. The experimental work with respect to five kinds of SMA-made cantilevered bending actuators (1L: the alone bar type; 2L: the parallel bar type; 4B: the bench bar type; 4Q: the quadrel bar type; 4S: the spool bar type) is performed. Two kinds of operating temperatures (one, the Af at 65℃ and below; the other, the Af at 71.1℃ and above) are adopted.

The first operating temperature with Af (65℃ and below) is used for both the alone bar type (1L) and the parallel bar type (2L) of the SMA-made actuators. The resultant loading and deflection is shown in Table 2. Also, under the second

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TABLE II
The resultant loading and deflection for the alone bar type (IL) and the parallel bar type (2L) actuators (Af=65℃ and below)

O.T.	Actuator	Alone Bar		Parallel Bar			Differ		Percent
	Symbol	1L		2L			(1L-2L)		%
65℃	P(g)	θ1(degree)	$\delta 1_{max(mm)}$	P(g)	θ2(degree)	$\delta 2_{max(mm)}$	Δθ= θ1-θ2	Δδmax= δ1max-δ2max	Δδmax/ 1L(δmax)
Load/ Deflection	5	3.01	4.21	10	3	4.19	0.01	0.02	0.48
	10	5.75	8.06	20	5.86	8.2	0.11	0.14	1.74
	15	8.47	11.92	30	8.67	12.19	0.2	0.27	2.27
	20	10.85	15.33	40	11.03	15.59	0.18	0.26	1.70
	25	13.27	18.87	50	12.82	18.2	0.45	0.67	3.55

TABLE III
The resultant loading and deflection for five kinds of actuators (Af=71.1℃ and above).

O.T.	Actuator	Alone Bar		Parallel Bar			Differ		Percent
	Symbol	1L		2L			(1L-2L)		%
71.1℃	P(g)	θ1(degree)	$\delta 1_{max(mm)}$	P(g)	θ2(degree)	$\delta 2_{max(mm)}$	Δθ= θ1-θ2	Δδmax= δ1max-δ2max	Δδmax/ 1L(δmax)
Load/ Deflection	5	2.08	2.84	10	2.01	2.81	0.07	0.03	1.06
	10	4.06	5.68	20	4.14	5.79	0.08	0.11	1.94
	15	6.2	8.69	30	5.95	8.34	0.25	0.35	4.03
	20	8.21	11.54	40	7.8	10.96	0.41	0.58	5.03
	25	10.18	14.37	50	9.82	13.85	0.36	0.52	3.62

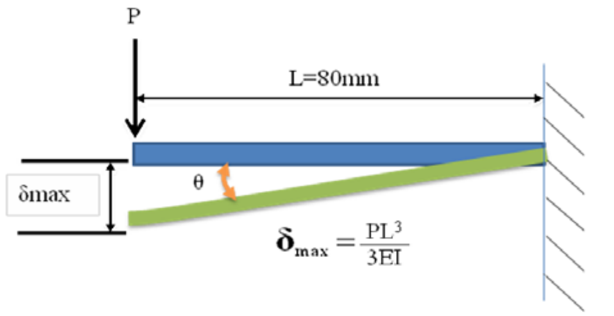

Fig. 7. The force model for a multi-wire SMA-made cantilever beam.

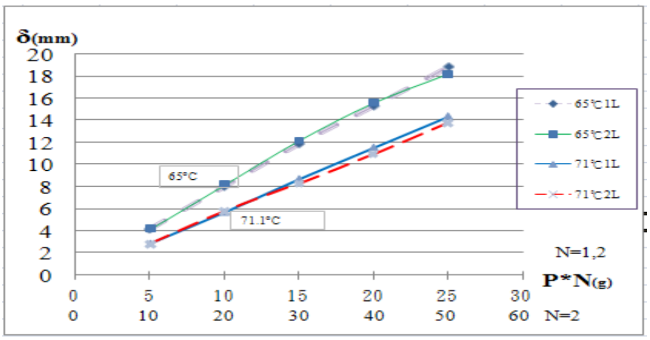

Fig. 8. The deflection with respect to loading at various operating temperatures (the alone bar type (1L) and the parallel bar type (2L) actuators).

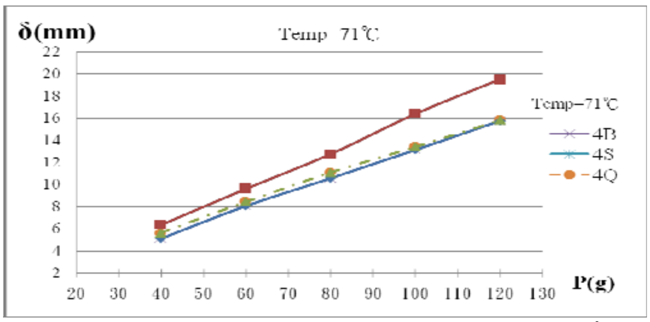

Fig. 9. The deflection with respect to loading operated at an Af of 71.1℃ for various actuators (the bench bar type (4B); the quadrel bar type (4Q); the spool bar type (4S) actuators).

operating temperature of Af (71℃ and above), the loading and deflection for the alone bar type (1L) and the parallel bar type (2L) are shown in Table 3. Moreover, with the same operating temperature, the loading and deflection for the bench bar type (4B), the quadrel bar type (4Q), and the spool bar type (4S) actuators are shown in Table 4. A comparison of the difference between the bench bar type (4B), the quadrel bar type (4Q), and the spool bar type (4S) are also shown in Table 5.

As indicated in Table 2, under the first operating temperature of Af (65℃ and below), the loading ability for a parallel bar type (2L) actuator with two SMA's wires is double that of the alone bar type (1L) actuator (with one SMA wire). When adding 25 (g) and 50 (g) onto these two actuators (1L and 2L), the difference of the bending angles between them is only 0.67mm.

Similarly, as indicated in Table 3, for the parallel bar type (2L) actuator, the displacement at the second operating temperature will be smaller by 4.35 mm than that of the first operating temperature. Therefore, for both the alone bar type (1L) and the parallel bar type (2L) actuators, the loading ability will increase and the displacement will decrease when the operating temperature is changed from an Af of 65℃ and below to an Af of 71.1℃ and above. As indicated in Fig. 8, for both the alone bar type (1L) and the parallel bar type (2L) actuators, the deflections within the same loading circumstance at an Af of 65℃ and below are larger than that of an Af of 71.1℃ and above. Likewise, as indicated in Tables 4 and 5, under the Af of 71.1℃ and above, for the bench bar type (4B), the quadrel bar type (4Q), and the spool bar type (4S) actuators, the related bending angles with respect to these three actuators at the same loading of 120 (g) is 11.41°, 11.19°, and 13.68°. Moreover, as indicated in Fig. 9, the deflections with respect to these three actuators at the same loading of 100 (g) is 13.13 (mm), 13.42 (mm), and 16.34mm. Therefore, there is a tendency that the different location-arrangements for the composite SMA-made actuators will result in different output forces. The inertia moment with respect to various sections of a multi-wire SMA-made actuator is shown in Table 6. The deflection formula of a cantilever beam is shown in Eq. (1). By plugging P, L, I, and δ into Eq. (1), the modules of elasticity (E) can be obtained.

$$\delta_{max}=PL^3/3EI \tag{1}$$

As indicated in Table 7, under the Af of 65℃, the modules of elasticity (E) for the alone bar type (1L) and the parallel bar type (2L) are 43.95 (GPa) and 43.79 (GPa). However, under the Af of 71.1℃, the modules of elasticity (E) for the alone bar type (1L) and the parallel bar type (2L) become 60.65(GPa) and 62.14 (GPa). Obviously, the modules of elasticity (E) for the alone bar type (1L) and the parallel bar type (2L) increase by one and half times when the operating temperature Af is changed from 65℃ to 71.1℃. As indicated in Fig. 10, under the Af of 71.1℃, the modules of elasticity (E) for the parallel bar type (2L) at various loadings are larger than 60 (GPa). Also, under the Af of 65℃, the modules of elasticity (E) for the parallel bar type (2L) at various loadings are below 48 (GPa). The difference of the modules of elasticity (E) for the parallel bar type (2L) reach 15.01 (GPa) when using two kinds of operating temperatures (71.1℃ and 65℃). As indicated in Table 8, for five kinds of four-wire actuators (the bench bar type (4B), the quadrel bar type (4Q), and the spool bar type (4S) actuators) operated at an Af of 71.1℃, the bench bar type (4B) has the largest modules of elasticity (E) (65.04 (GPa)), and the spool bar type (4S) has the smallest modules of elasticity (E) (54.07 (GPa)). Table 8 indicates that because of the unparallel arrangement effect for the spool bar type (4S) actuator, the interference between the wires may be serious and might result in a lower rigidity. Also, as indicated in Fig. 11, the modules of elasticity (E) for the bench bar type (4B) and the quadrel bar type (4Q) are similar. The module of elasticity (E) for the spool bar type (4S) actuator is lower by10.97 (GPa) on average than other actuators.

Moreover, an intersect point of the two curves (one for the bench bar type (4B) and the other for the quadrel bar type (4Q)) occurs at the loading of 100 (g). The module of elasticity (E) for the quadrel bar type (4Q) will be larger than that of the bench bar type (4B) because of the stacking effect of the four wires.

Summarizing the loading data and the related deflection for the alone bar type (1L), the parallel bar type (2L), and the bench bar type (4B), the corresponding profiles operating at an Af of 71.1℃ are plotted in Fig. 12. The x-axis represents the multiplication of loading (P) and the wire number (N). The wire number (N) for the alone bar type (1L), the parallel bar type (2L), and the bench bar type (4B) are one, two, and four. Results reveal that even though the bench bar type (4B) is four times the alone bar type (1L) in N, the difference of deflection between these two actuators is only 1.24 (mm). It has been found that the module of elasticity (E) of the SMA-made actuator is proportional to the number of wires (N). Also, the deflection of the SMA-made actuator is inversely proportional to the number of wires (N).

Moreover, the profiles of deflection and loading with respect to five kinds of actuators are summarized in Fig. 13. As indicated in Fig. 13 the spool bar type (4S) actuator is more flexible than the other actuators.

TABLE IV
The resultant loading and deflection for three kinds of actuators

O.T.	Actuator	Bench Bar		Spool		Quadrel	
	Symbol	4B		4S		4Q	
71.1°C	P(g)	θ1(degree)	$\delta1_{max(mm)}$	θ2(degree)	$\delta2_{max(mm)}$	θ3(degree)	$\delta3_{max(mm)}$
Load/ Deflection	40	3.82	5.13	4.54	6.36	4.02	5.62
	60	5.78	8.07	6.86	9.62	6.02	8.43
	80	7.62	10.58	9.06	12.75	7.88	11.07
	100	9.49	13.13	11.58	16.4	9.53	13.42
	120	11.41	15.74	13.68	19.47	11.19	15.82

TABLE V
The comparison of loading and deflection for 4B, 4Q and 4S of actuators.

O.T.	Actuator	Differ				%			
	Symbol	(4B-4Q)=M1		(4B-4S)=M2		M1		M2	
71.1°C	P(g)	Δθ= θ1-θ3	Δδmax= δ1max-δ3max	Δθ= θ1-θ2	Δδmax= δ1max-δ2max	Δθ/4B(θ)	Δδmax/ 4B(δmax)	Δθ/4B(θ)	Δδmax/ 4B(δmax)
Load/ Deflection	40	0.2	0.49	0.72	1.23	5.24	0.10	15.86	0.19
	60	0.24	0.36	1.08	1.55	4.15	0.04	15.74	0.16
	80	0.26	0.49	1.44	2.17	3.41	0.05	15.89	0.17
	100	0.04	0.29	2.09	3.27	0.42	0.02	18.05	0.20
	120	0.22	0.08	2.27	3.73	1.93	0.01	16.59	0.19

TABLE VI
The inertia moment for the actuators

Diameter of SMA's wire	L	R (SMA's cross sectional diameter)	Number of wires	I(Inertia moment)= $\pi R^4/4$	Arrange pattern
0.001m	0.08m	0.0005m	1	4.908 E-14 m^4	
			2	9.817 E-14 m^4	
			4	1.963 E-13 m^4	

TABLE VII
The resultant modulus of elasticity and loading for two kinds of actuators.

Actuator	Alone Bar		Parallel Bar	
Symbol	1L		2L	
O.T. 65°C	P(g)	E(GPa)	P(g)	E(GPa)
	5	41.26	10	41.47
	10	43.16	20	42.38
	15	43.77	30	42.79
	20	45.47	40	44.59
	25	46.12	50	47.76
AVG_E		43.95		43.79

B. *Discussion*

It has been seen that the actuator force will increase when the number of wires increase and the operating temperature is increased to 71.1°C. Moreover, the effect of the arranged pattern for multiple wires is an essential factor in influencing the actuator's output force.

Summarizing the data of Tables 3 and 4 and using the least-square-root method, the regressive mathematical forms of the deflection and the loading for various actuators are expressed as the following:

Alone bar type actuator (1L):

$$\delta = -0.547+0647P-0.001P^2 \quad (2)$$

Parallel bar type actuator (2L):

$$\delta = -1.29+0.417P+0.003P^2 \quad (3)$$

Bench bar type actuator (4B):

$$\delta = 1.123+0.666P-0.003P^2 \quad (4)$$

Spool type actuator (4S):

$$\delta = -0.717+0.528P+0.003P^2 \quad (5)$$

Quadrel type actuator (4Q):

$$\delta = -0.744+0.681P-0.004P^2 \quad (6)$$

TABLE VIII
The resultant modulus of elasticity and loading for five kinds of actuators

Actuator	Alone Bar		Parallel Bar		Bench Bar		Spool	Quadrel
Symbol	1L		2L		4B		4S	4Q
O.T. 71.1°C	P(g)	E(GPa)	P(g)	E(GPa)	P(g)	E(GPa)		
	5	61.25	10	61.85	40	65.03	54.73	61.87
	10	61.25	20	60.07	60	64.42	54.25	61.87
	15	60.01	30	62.55	80	64.99	54.52	62.82
	20	60.24	40	63.46	100	65.01	53	64.75
	25	60.51	50	62.77	120	64.6	53.57	65.93
AVG_E		60.65		62.14		64.81	54.014	63.448

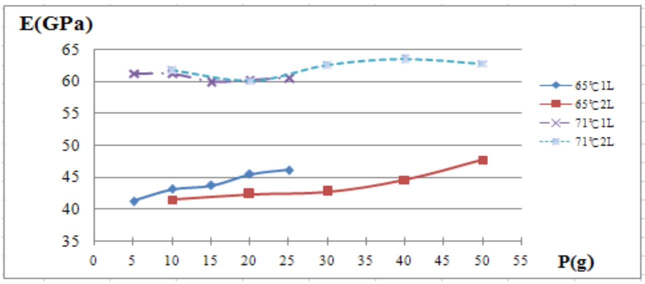

Fig. 10. The modulus of elasticity with respect to loading at various operating temperatures

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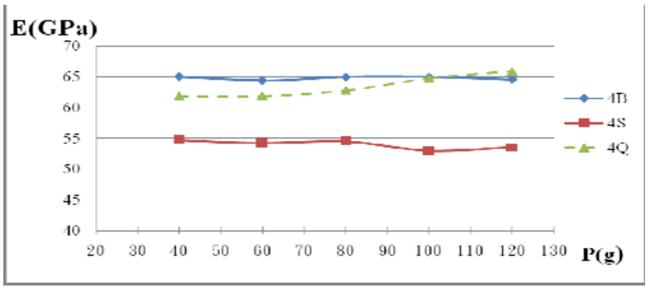

Fig. 11. The modulus of elasticity with respect to loading operated at an Af of 71.1℃ for various actuators

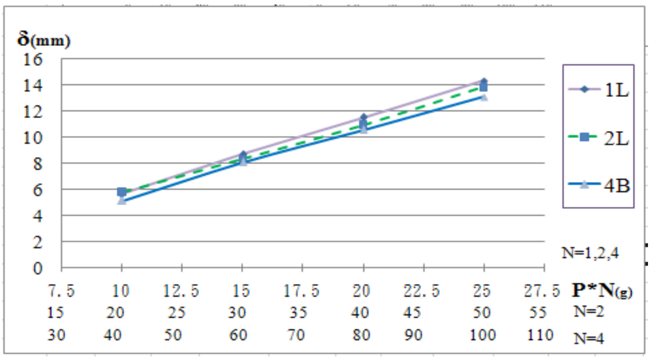

Fig. 12 The deflection with respect to loading operated at an Af of 71.1℃ for various actuators

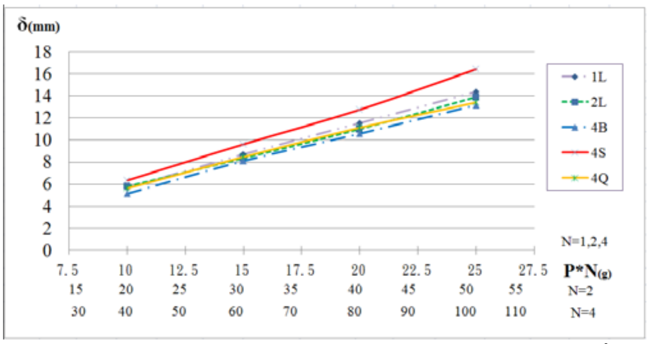

Fig. 13. The deflection with respect to loading operated at an Af of 71.1℃ for various actuators

V. CONCLUSION

A $Ti_{50}Ni_{45}Cu_5$ (1.0 mm in φ and 0.12 m in length) is adopted in the SMA-made actuator. As indicated in Fig. 1, five kinds of arrangements for SMA wires (1L: the alone bar type; 2L: the parallel bar type; 4B: the bench bar type; 4Q: the quadrel bar type; 4S: the spool bar type) are proposed. The mathematical forms of multiple-wire SMA-made bending actuators using experimental data in conjunction with the regressive method are listed below:

1) For the alone bar type (1L) actuator operated at an Af of 71.1°C, the mathematical form of loading (P) with respect to deflection (δ) is:

$$\delta=-0.0012+0.557(P)-0.0003(P^2) \quad (7)$$

2) For the multi-wire actuators (2L: the parallel bar type; 4B: the bench bar type; 4Q: the quadrel bar type; 4S: the spool bar type) operated at an Af of 71.1°C, the general mathematical form of loading (P) with respect to deflection (δ) is summarized as:

$$\delta=(-0.0012+0.557P-0.0003P^2)*(k/N) \quad (8a)$$

k (for 2L: the parallel bar type) =0.9789; (8b)

k (for 4B: the bench bar type) =0.92118; (8c)

k (for 4S: the spool bar type) =1.125; (8d)

k (for 4Q: the quadrel bar type) =0.969; (8e)

Where k is the factor of the wire arrangement, and N is the number of wires for various actuators.

Under the operating temperature of an Af of 71.1℃ and the actuator length of 0.08 (M), the maximum loading, bending moment, and deflection for the alone bar type (1L) actuator are 0.025 (N), 0.02 (Nm), and 14.37 (mm). For the parallel bar type (2L) actuator, the related maximum loading, bending moment, and deflection are 0.05 (N), 0.04 (Nm), and 13.85 (mm). Moreover, the maximum loading, bending moment, and deflection for the bench bar type (4B) actuator are 0.12 (N), 0.096 (Nm), and 15.74 (mm). Also, the maximum deflections of the spool bar type (4S) and the quadrel bar type (4Q) are 19.47 (mm) and 15.82 (mm).

Therefore, the experimental data in this study is confirmed to be reliable. Consequently, to improve the output force of a SMA-made dynamic splint used for a finger joint, various multi-wire SMA-made actuators can be considered depending upon each patient's requirement

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