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An experimental investigation on shape memory alloy dynamic splint for a finger joint application

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ABSTRACT

To strengthen fingers which are injured in an accident, a new type of SMA (shape memory alloy)-made dynamic splint used for finger joints is proposed.

The issue, here, is to clearly present the mechanism and control system of the dynamic splint. Four wires of the shape memory alloy (SMA – $Ti_{50}Ni_{45}Cu_5$ with 1.0 mm in Φ) are arranged in parallel within silica-gel tubes. The finger glove made of six pieces of silica-gel tubing, which abare parallel to the fingers, is a flexible joint that moves during rehabilitation when the SMA is heated. Two kinds of dynamic splints (one, a fixed-type dynamic splint; and the other, a portable-type dynamic splint) are developed. The former, which has an adjustable mechanism to fit various fingers using a PC-based control system, is suitable in a medical clinic milieu. The latter, controlled by a microcontroller (PIC18F452), is suitable for home rehabilitation. Both splints incorporate the SMA's temperature-feedback system that keeps them within the appropriate safety range. The output force of the SMA-made dynamic splint develops in this study is 22 N that is sufficiently used in the rehabilitation.

1. Introduction

The human hand is a complicated system with several functions: catching, holding, pinching, carrying, and clipping that perfect motion consists of the tendon, ligament and finger bones combinative [1]. The friction force induced by the joint angle and the pulley tendon will influence the recovery of the forefinger joint [2].

Thus, injury to a tendon often occurs in an accident. Sutures are used for the pulley tendon when the flexor tendon or the extender tendon is broken [3]. The method of rehabilitation for the injured flexor tendon will also influence the recovery time. Appropriate rehabilitation will speed up the recovery time and lower sequelae that result from surgery. A common passive rehabilitation utilizes a bending force generated by the splint [4]. Therefore, to improve the rehabilitation process, the selection of an appropriate splint is essential.

In the past decade, various dynamic models and calculations for robotic fingers and artificial limbs have been used to analyze finger characteristics [5–7]. Apparently, three joints are responsible for finger flexibility. A motor in conjunction with a wire and a pulley is used to provide four degrees of motion, including flexion/extension and abduction/adduction. The force transmission of the mechanism can be adjusted and controlled actively or passively via a feedback sensor on the forefinger [5,8]. To ensure flexibility, the motion of the finger joints is separate [9–11]. Additionally, the linear motor control transmitted by a pulley/wire mechanism, one kind of continuous passive motion (CPM), has been widely used as the rehabilitation force and angle control for the finger after surgery has been completed [12]. Here, the DC motor in conjunction with a Hall sensor used for the feedback control of the angle and force can provide 0.92 Nm for a metacarpalphalange joint (MP), 0.21 Nm for a proximal interphalangeal joint (PIP), and 0.31 Nm for a distal interphalangeal joint (DIP) [13]. Formerly, to provide sufficient force for rotation or linear motion, traditional motors have been used. However, they are heavy, complicated, and inconvenient. Therefore, a SMA-made actuator which is frictionless and quiet has been developed [7,14].

Two types of SMA-made actuators ($Ti_{50}Ni_{45}Cu_5$ and $Ti_{50}Ni_{50}$) have been assessed. For the former one ($Ti_{50}Ni_{45}Cu_5$), the SMA material will remember the original shape when bent at a specific high temper region; therefore, the SMA material will be stretched or bent to the original shape when it is heated at the specific temperature. However, for the latter one ($Ti_{50}Ni_{50}$), the SMA material will be shrink only by 6% when it is heated. Therefore, the $Ti_{50}Ni_{45}Cu_5$-made SMA actuator is adopted in this study.

Moreover, the SMA-made actuator can be applied within the confines of a small moving structure. For a cantilever beam, the $Ti_{50}Ni_{45}Cu_5$ SMA-made actuator can be embedded in the beam and used to precisely control the position [15,16]. It has been found that a sufficient clipping force can be achieved using a SMA-made

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microgripper in conjunction with a hinge [17]. Some medical equipment, such as the bladder and the stomach, operates within a narrow space. The design of the capsule's shape in conjunction with a multi-linkage bending mechanism derived from a SMA has often been used in the kinetic control of movement and position allocation [18,19]. An artificial limb can be rendered flexible using a SMA-made actuator linked with a splint [20]. To improve the drawbacks of traditional finger rehabilitation, a SMA-made actuator which is compact, sensitive to temperature, and convenient to operate has been incorporated into the finger rehabilitation device.

In this study, the driven force of the SMA-made actuator will be triggered by heating the SMA wire via the electrical circuit. In order to prevent the SMA from overheating, the SMA temperature will be detected by using a thermocouple embedded in the SMA. The driven force from the SMA-made actuator will serve as the rehabilitation force of the dynamic splint. Because the driving force is proportional to the Young's module (*E*), the increment of the heating temperature will result in a higher *E*. Here, the SMA-made actuator will be heated beyond Af (the ending transformation temperature for Austensite). Therefore, a new type of an SMA-made dynamic splint used for full finger joints has been developed and found to be suitable as an actuator for finger rehabilitation.

2. Methods

2.1. Shape memory alloy

Because the $Ti_{50}Ni_{45}Cu_5$-made SMA material will remember the original shape when bent at a specific high temperature, it will be stretched or bent to the original shape when it is heated at the specific temperature again. Therefore, the $Ti_{50}Ni_{45}Cu_5$ (1 mm in Φ) is adopted in this study. As indicated in Table 1, the $Ti_{50}Ni_{45}Cu_5$-made SMA is very sensitive for temperature.

The shape-memory effect for the alloy will occur via the transformation of the crystal structure from the Austensite (at a lower temperature) to Martensite (at a higher temperature) when the alloy is heated. Meanwhile, the stiffness (*E*) will be increased and the original shape of the alloy will be recovered during the heating process. As indicated in Fig. 1, the alloy can be bent in any shape in normal temperature. The shape of the SMA can be fully recovered to its original shape (stretched shape) via the complete phase transformation. Similarly, the alloy will be turned back to the bent shape when the SMA is cooling down to the Mf and below. To speed up the SMA's response, the electrical circuit will increase.

Table 1
The characteristic properties for the SMA.

$Ti_{50}Ni_{45}Cu_5$ SMA	
As (the starting transformation temperature for Austensite)	315 K (42 °C)
Af (the ending transformation temperature for Austensite)	340 K (67 °C)
Ms (the starting transformation temperature for Martensite)	320 K (47 °C)
Mf (the ending transformation temperature for Martensite)	293 K (20 °C)
Hysteresis	18 (K)
Maximum deformation rate (γ)	6 (%)
Heat expansion coefficient (α)	10^{-1} (K^{-1})
Density (*D*)	6650 kg/m^3
Elastic constant (*E*)	40–65 GPa

The SMA-made actuator includes two types of rehabilitation forces (stretching force and shrinking force). If the original SMA shape is a straight line at a specific high temperature, the SMA will record the shape; therefore, the stretching force will occur when the SMA is heated at the Af and above. On the contrary, if the original SMA shape is bent at a specific high temperature, the SMA will record the bent shape. The shrink force for rehabilitation will occur when the SMA is heated at the Af and above again. Here, the rehabilitation force of a stretching force using a SMA-made actuator is assessed.

2.2. Structure of finger

A hand is composed of 27 bones including 8 carpal bones, 5 metacarpal bones, 5 proximal phalanges, 4 middle phalanges, and 5 distal phalanges. As indicated in Fig. 2, each finger includes three phalanges, including a proximal phalanx, middle phalanx, and distal phalanx. A joint exists between the phalanges. There is a metacarpalphalange joint (MP), a proximal interphalangeal joint (PIP), and a distal interphalangeal joint (DIP). Here, the angles of flexion/extension for MP, PIP, and DIP are 90°, and 80° [21,33].

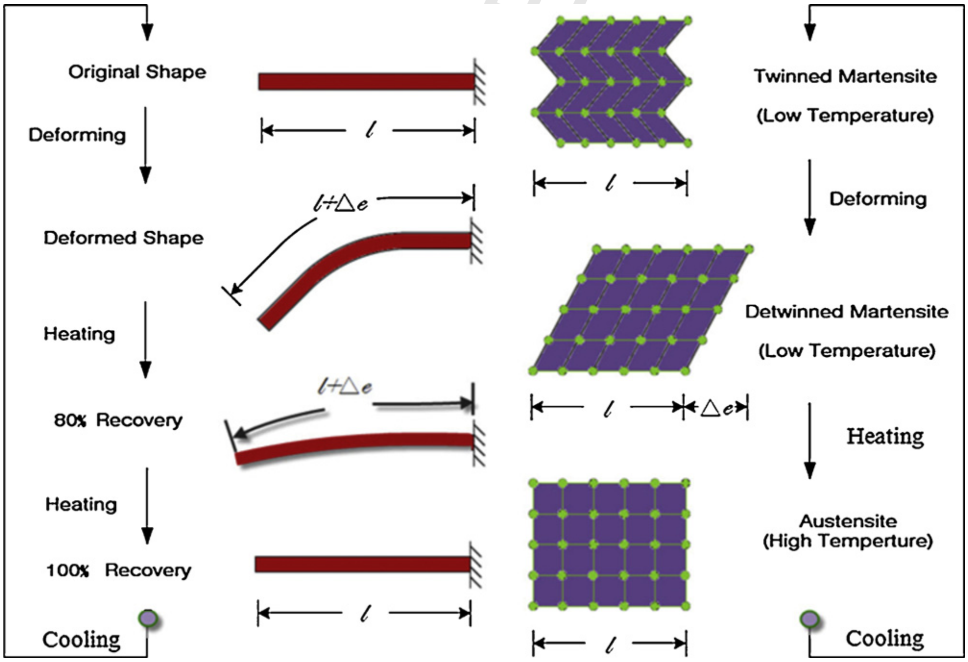

Fig. 1. Memory effect of bending recovery process.

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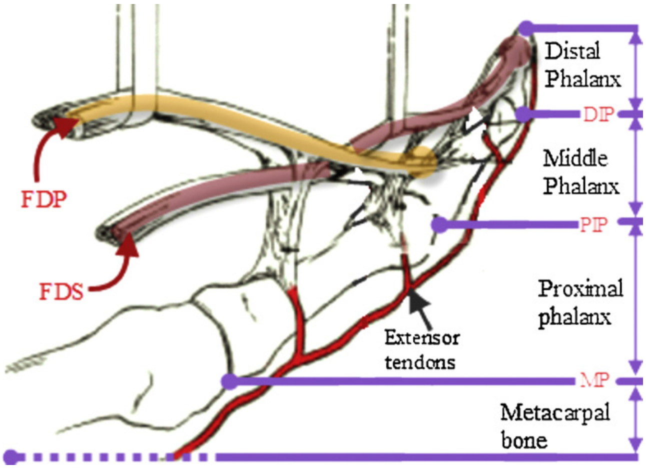

Fig. 2. Structure of the finger an flexor tendons with attached vincula [30].

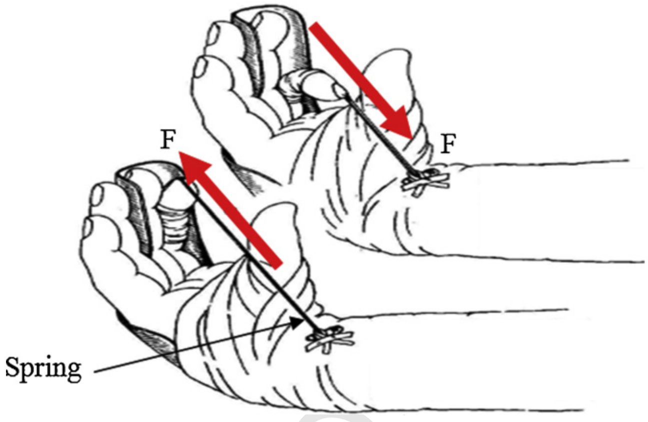

Fig. 3. The dynamic splinting in the index finger [23,30–32].

As indicated in Fig. 2, the ligament of a tendon in the finger includes the flexor tendon and the extender tendon for a metacarpophalangeal point. In addition, the flexor tendon of the fingers is located at the front surface of the palm. The muscle is extended from the end of the front limb to the end of the finger. They are wrapped by the epitenon membrane and the pulley ligament. Moreover, the extender tendon of the fingers is located at the back surface of the palm. It stretches the finger. The muscle is extended from the front limb to the finger.

There are two groups of the muscles (intrinsic muscles and extrinsic muscles) which manipulate the grasping function of a hand. The intrinsic muscles include the dorsal interosseous, the palmar interossei, and the lumbrical. The extrinsic muscles are composed of flexor digital profundus (FDP) and flexor digital superficialis (FDS) shown in Fig. 2. The near end of the FDP is located at the cross point of the ulna and elbow joint. The far end of the FDP is allocated from the second distal phalanx to the fifth distal phalanx. Similarly, the near end of the FDS is located at the cross point of the ulna and the elbow joint. The far end of the FDP extends from the second middle phalanx to the fifth middle phalanx. According to the placement of FDP and FDS, it is obvious that the FDP is the only muscle which can manipulate the distal interphalanges joint (DIP). However, the action for the proximal interphalange joint (PIP) is controlled by both FDP and FDS [22–24].

2.3. Rehabilitation process and splint

Medical treatment for an injury to a hand is essential for a clinical surgeon. The injuries of a hand include a broken phalanx, a damaged flexor tendon and extender tendon, and cut fingers [25]. Here, the injury to a flexor tendon quite often occurs. The first step in treatment is suturing. The suturing methods, such as Mason-Allen, Becker bevel, and Kessler are developed [26]. Not only suturing techniques but also the suturing material will influence the strength of the flexor tendon after surgery. Currently, the suturing wire used in surgical operations is No. 3-0 and No. 4-0 and is made of an Ethibond suture [27,28].

After surgery, there are three stages within the rehabilitation period, including: (1) inflammation stage (zero to five days after surgery), (2) fibre developing stage, (five to twenty-one days after surgery), and (3) rebuilding stage (three to twelve weeks after surgery). Here, both the first and the second stages are used to protect the tendon from breaking and adhesion. The third stage is aggressive rehabilitation for the tendon and lasts from twelve to sixteen weeks [25,27,29]. There are also various methods at the beginning of medical treatment such as surgery, in plasters, 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. A static splint used in the first and second stages to prevent the tendon from being severed due to excessive motion is required [27]. Nevertheless, tendon adhesion and an increasingly deformed tendon will occur. These can result in a deformed finger, a lack of motion for the active/passive joint, a shrinking of the joint, or a weakening of the tendon [25]. To overcome these drawbacks, as indicated in Fig. 3, Kleinert developed a series of dynamic splints [23,30–32] in 1970. The principle of the dynamic splint is to provide a dynamic and passive actuating motion. A reciprocating force is derived from the adhesion and the wire tension (rubber band). In addition, an appropriate range of the reciprocating force that prevents the tendon from being injured is selected. Two methods of healing for a finger are found when using a dynamic splint in the rehabilitation process: one is intrinsic healing and the other is the extrinsic healing [23,29]. For intrinsic healing, an appropriate pulling force that is applied to the tendon and will not injure the tendon increases the rate of blood flow within the joint and speeds up the process of metabolism. Therefore, the healing of the tendon will improve. Similarly, for extrinsic healing, adhesion by the tendon will be improved and abnormal scaring will be decreased [24].

From a bioengineering perspective, the allowable maximal rehabilitation force manipulating the flexor digital profundus (FDP) and the flexor digital superficialis (FDS) [30,33,34] is 22 N; therefore, the goal of the SMA bending actuator is to design a force of 22 N for the dynamic rehabilitation of the finger driven by dynamic splint.

At the first stage of the rehabilitation process, the dynamic splint can provide an auxiliary force to the finger joint to keep moving and avoid adhesion. At the last stage of the rehabilitation process, the dynamic splint will provide the joint a resistance force that will give the ligament and the tendon a sufficient training to recover its original function. In this study, on the basis of practical clinical requirement, the mechanism design for rehabilitation dynamic splint is established using the SMA-made actuator.

2.4. Design of dynamic splints

The reciprocating force for a tradition dynamic splint is derived from the adhesion and the wire tension (rubber band). Because of the difficulty in adjusting the rubber band's tension, a rehabilitation force using a SMA-made actuator is developed.

In this study, the author's fingers used in the rehabilitation program are preset. An index finger 0.12 m in length (from distal phalanx to metacarpal bone) is measured. As indicated in Fig. 4(a),

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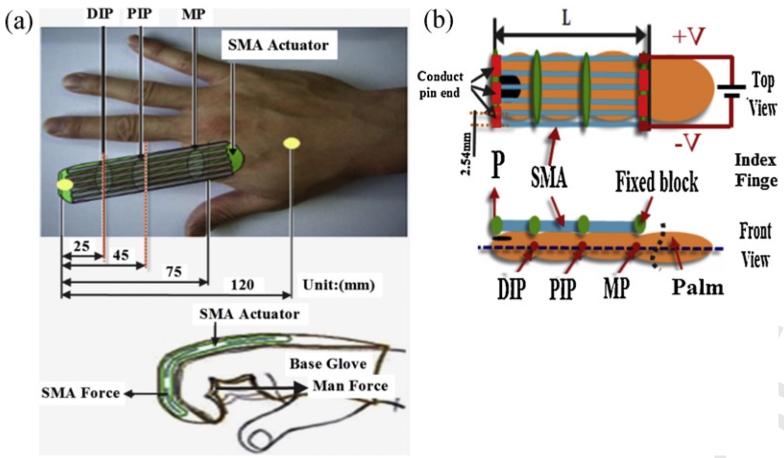

Fig. 4. SMA-made actuator layout for a finger. (a) SMA layout for the index-finger. (b) SMA-made actuator (Φ 0.6 mm, L 0.06 m).

the length of the distal interphalangeal joint, the proximal interphalangeal joint, and the metacarpophalangeal joint are 0.025 m, 0.045 m, and 0.075 m.

First, as indicated in Fig. 4(b), six pieces of $Ti_{50}Ni_{45}Cu_5$ (0.6 mm in Φ and 0.06 m in length) are parallel to each other and span 2.54 mm. The fixed block for the SMA's wire has been placed at the joints. The SMA-made actuator has been heated using a series of connection with pins. To assess the practical swinging angle and the related heating temperature (Ts) at various loading forces, a series of experimental processes in detecting the above data using an image-captured detecting system via a web camera in conjunction with the Microsoft Visual Basic 6.0 (VB 6.0) interface has been established. Results reveal that the assistant force provided by the SMA-made actuator is about 1 N. For dynamic tendon rehabilitation, 22 N for the finger's tendon are necessary. So, the rehabilitation device shown in Fig. 4(b) is insufficient.

Therefore, a new and improved SMA-made finger splint using a SMA of 1.0 mm in Φ and 110 mm in length is employed. Four wires of the shape memory alloy are bounded and arranged in parallel within the silica-gel tubes shown in Fig. 5(a) (2 mm in the inner Φ and 4 mm in the outer Φ). Here, to reach a good thermal insulation, the silica-gel tube is adopted. Six pieces of the silica-gel tubing are linked with a fixed block which is adjustable upon the patient's requests (Fig. 5(b)). Moreover, a finger glove made of six pieces of the silica-gel tubing, which are parallel to the fingers, has a flexible joint motion during rehabilitation when the SMA is heated shown in Fig. 5(c).

As indicated in Fig. 6(a), a fixed-type dynamic splint used in the rehabilitation of the finger joint is established (dimensions are 0.17 m in high, 0.07 m in width and 0.15 m in length). The functions used in fitting various finger sizes, adjusting the SMA-made bending actuator by loosening the screw on the upper/side and micro-adjusting the nut on the rear are required. To match various thicknesses of a rehabilitation palm, as indicated in Fig. 6(b), the patient can, by altering the copper-made nut on the left, adjust both the upper and lower plate that are used to fix the palm. The function of the fixed-type dynamic splint is similar to the initial stages of rehabilitation process used in clinics.

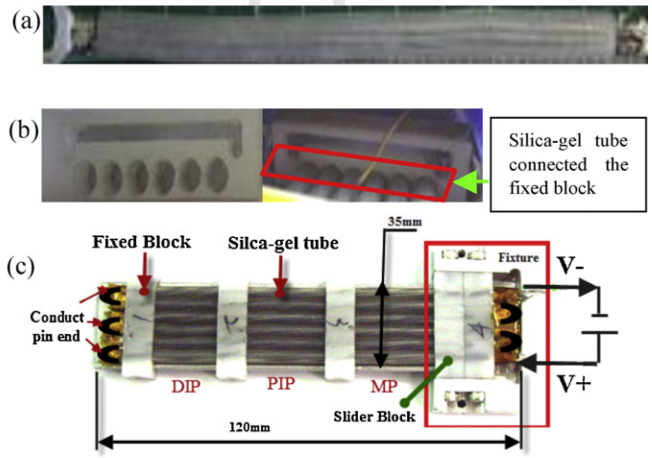

Fig. 5. SMA-made actuator, (a) SMA actuator silica-gel tube. (b) SMA fixed block. (c) The SMA-made actuator features (Φ 1.0 mm, L 0.12 m actuator).

For convenient use at home, a portable type dynamic splint is developed. The rehabilitation device with light weight has multiple chooses. Here, as shown in Fig. 7(a), the SMA-made bending actuator is fixed at the sliding slot. Thereafter, the sliding block is adjusted at the rehabilitation position by locking it with a screw

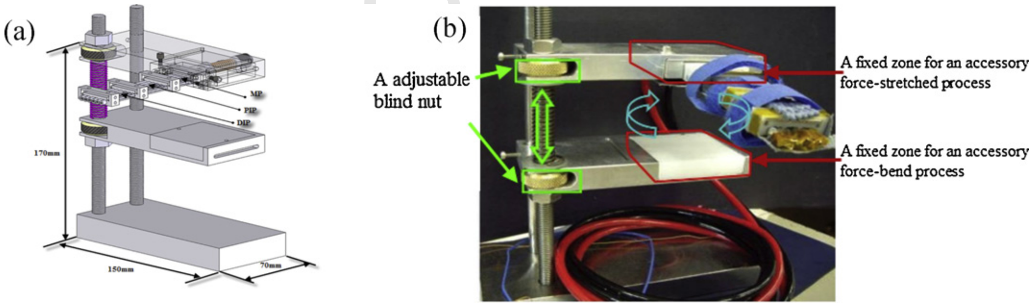

Fig. 6. The fixed-type dynamic splint for fingers. (a) 3-D structure of fixed-type dynamic splint. (b) Adjustment of the upper and lower plates to meet the thickness of the patient's.

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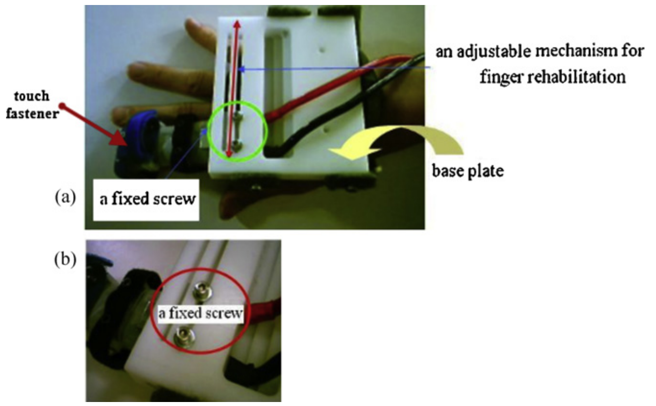

Fig. 7. Portable type dynamic splint. (a) Glove like dynamic splint with a SMA-made actuator; (b) sliding block that can be fixed at the position of any fingers.

shown in Fig. 7(b). The device can adjust the suitable position of any fingers to do the rehabilitation treatment. After putting the glove on the back of the palm, plugging the finger in via the touch fastener, the rehabilitation for bending the finger's tendon shown in Fig. 7(a) is ready for operation. The extender tendon can be manipulated when the SMA-made actuator is placed on the lower side of the rehabilitation glove.

To facilitate the operation of a compact and portable actuator, a microcontroller (PIC18F425) was used to control the alternating current (AC) power that controls the temperature of the SMA is required. Additionally, the phase signal of AC 110 V 60 Hz is detected and will be transformed into a digital pulse (60 Hz). According to the 60 Hz pulse, the microcontroller can switch the AC power output to the SMA actuator by using a TRIAC (tri-electrode-alternating current) synchronously. Here, a thermal couple is connected to the analog and the digital (A/D) converter allowing the microcontroller to read the SMA temperature. Thereafter, the microcontroller can control the temperature of the SMA-made actuator within two operation temperature (50–55 °C).

2.5. Experimental setup

The maximum performance of the rehabilitation force and angle with respect to the operating temperature manipulated by the SMA is critical.

As indicated in Fig. 8(a), the SMA-made actuator is bent 90° against a pushing gauge (i.e., scale = 50 g, maximum = 3 kg). An angle-measuring instrument is put on the pushing gauge to serve as a horizontal calibrator. Thereafter, the SMA-made actuator will deform when it is heated. The pushing force from the actuator will be recorded by the pushing gauge. In our experiment, the SMA-made actuator is heated up to 50–55 °C using the electrical circuit (SMA wires heated up approximately 70 ± 1 °C).

As indicated in Fig. 8(b), to access an experimental measurement, a PC-based control system programmed by VB language is established. The temperature of the SMA can be read via the (recommended standard-232) RS-232 protocol. The thermocouple used in the study is TPT-01-36G T type. Its accuracy is ±0.05 °C within the temperature range of −200 to 1370 °C.

To obtain the operating temperature (Ts), two thermocouples are connected at the inside SMA wires/outside silica-gel tube's surface temperatures of the SMA-made actuator. The detecting node for outside temperature is preset between the third and the fourth surface of the actuator silica-gel tubes. Also, the temperature of the inner actuator tube, the real temperature of the SMA, is detected by using a thermocouple embedded inside the actuator tubes as shown in Fig. 9(a).

The operation temperature of SMA-made actuator is limited to 50–55 °C measurement on the surface of the silica-gal tube that system will be turned off if its temperature exceeds 55 °C. In order to assure the safety of the SMA-made actuator and to easily detect the operating temperature, a thermal feedback system is engaged by obtaining the temperature difference between

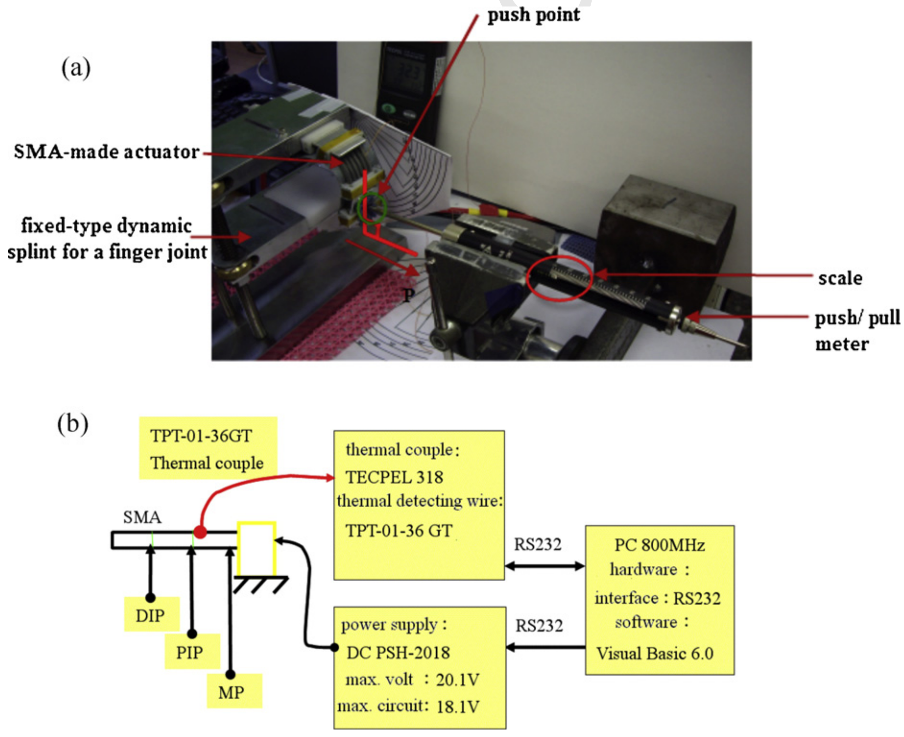

Fig. 8. Experimental setup. (a) The testing plate for the fixed-type dynamic splint; (b) the block diagram of measuring system of the SMA-made dynamic splint.

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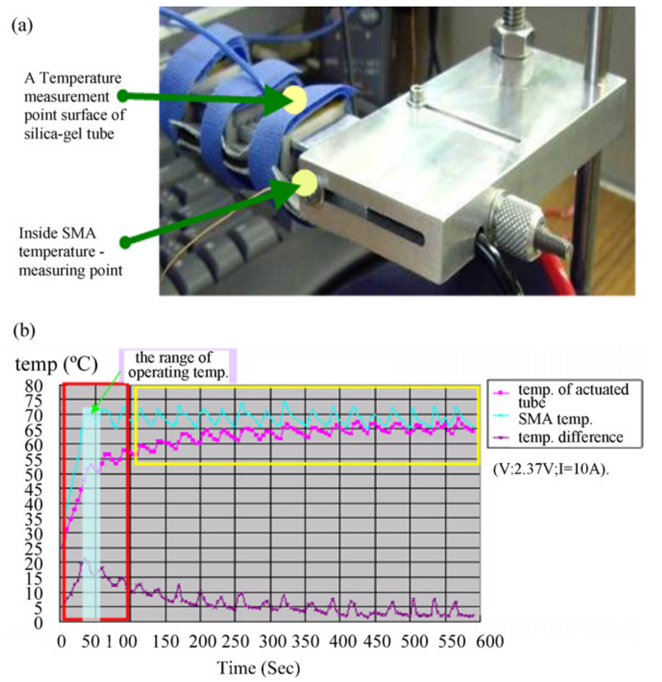

Fig. 9. The real-time detected dynamic temperature of the SMA. (a) The temperature measuring points. (b) The dynamic temperature curve of the inside SMA wires and surface of silica-gel tube.

the SMA's working temperature and the silica-gel tube's surface temperature.

The temperature experiment is shown in Fig. 9(b). Here, the unit of the *x*-axis is time in *T* (s) and the unit of the *y*-axis is temperature in °C (Celsius degree). The related electrical voltage and circuit are 2.37(V) and 10(A). The temperature of the SMA wire will be online controlled within 66–70 °C via a thermocouple. The electrical power will be turned on when the temperature of the SMA is online detected as 66 °C and below via the thermocouple. On the contrary, the electrical power will be turned off when the heated temperature of the SMA reaches 70 °C and below.

Three profiles represent the SMA wires, the actuated surface of silica-gel tube, and the difference in temperature, respectively. The initial temperature is 28 °C. The temperature will be recorded per 5 s. The total time for heating is 650 s. The temperature difference reaches 20 °C when the SMA is heated for 10–12 s. This means that the temperature of the SMA will reach 70 °C when the silica-gel tube's surface temperature of the actuator reaches 50–55 °C. Therefore, the electrical power will be turned off when the silica-gel tube's surface temperature of the actuator reaches 50–55 °C. It is found that for the heating zone from time = 100 s to time = 400 s, the profile of the SMA's temperature becomes steady after time = 100 s. The temperature of the SMA will rise rapidly when the electrical circuit is added. However, because of the insufficient cooling effect in the silica-gel tube during the cooling process, a ripple shown in Fig. 9(b) will occur. The temperature of the silica-gel tube surface temperature will increase until time reaches 400 s. The difference between the SMA wires and the silica-gel tube's surface temperature is 4.3 °C.

The rehabilitation will be restarted when the surface temperature of the silica-gel tube is cooled to 30 °C. Moreover, the heating rate will increase when the electrical circuit increases. On the other hand, the instant output force will decrease if the electrical voltage is tuned down. Therefore, the electrical voltage can be increased if a fast rehabilitation cycle is required; however, the instant output force will increase suddenly. Also, choosing the temperature of the silica-gel tube at 50–55 °C is suitable for the hot packs used by the patient during the finger's rehabilitation process.

Additionally, for practical purposes, the operating frequency of the rehabilitation is five times per minute [24,27,30,34]. To increase the rehabilitation frequency, the electrical voltage can be increased.

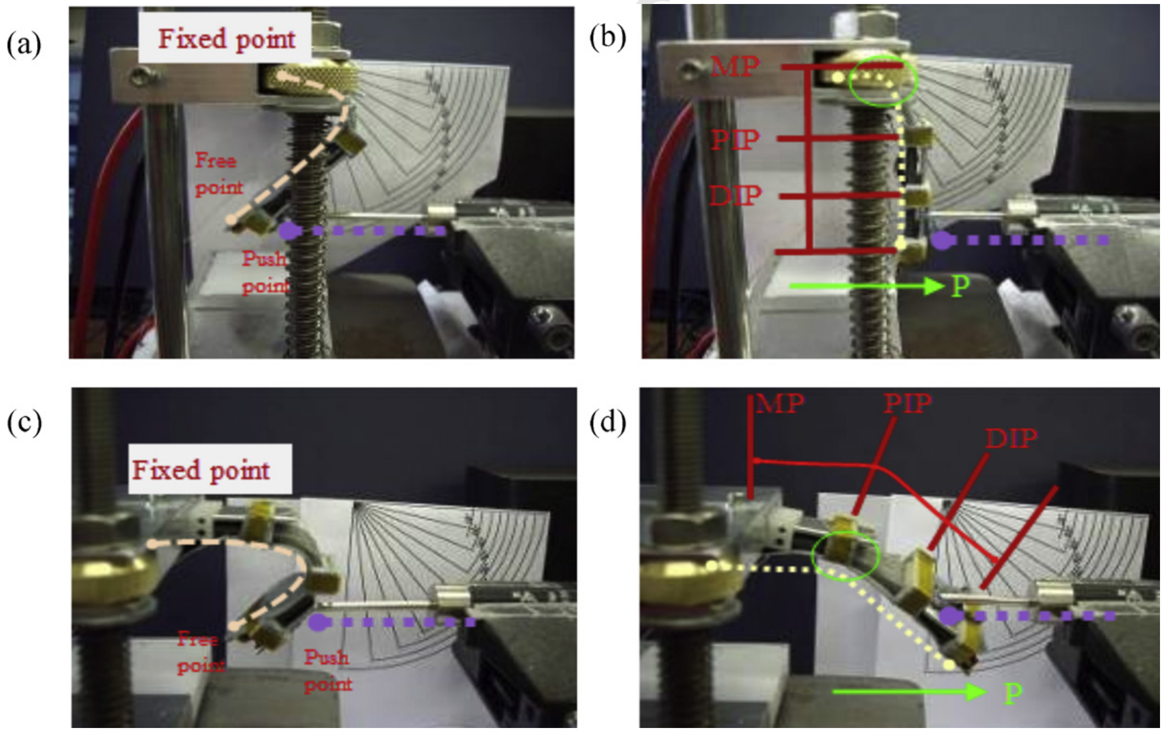

Fig. 10. The output force testing for the SMA-made actuator. (a) SMA-made actuator with a length of 70 mm (MP) is pre-bent to an angle of more than 90° and attached to the pushing force gauge. The driving force on MP can be measured. (b) The MP output force at 90° is measured as 20 N. (c) SMA-made actuator with a length of 50 mm (PIP) is pre-bent to an angle of more than 90° and attached to the pushing force gauge. The driving force on MP can be measured. (d) The PIP output force at 90° is measured as 30 N.

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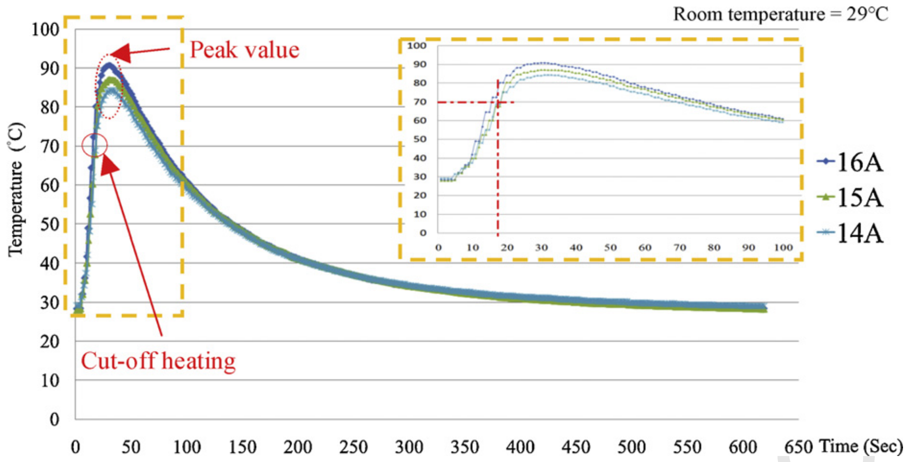

Fig. 11. The time responses of the SMA's heating and cooling processes with respect to various electrical circuits.

Table 2
The output force and bending moment for two kinds of SMA-made actuators with various lengths (one, 50 mm in length; and the other, 70 mm in length).

Length of a SMA-made actuator (m)	Finger joint	Angle (degree)	Load (N)	Heating time (s)	Bending moment (Nm)	Ampere (A)	Apply voltage (V)
0.07	MP	90	20	18.1	1.4	14	3.30–3.50
		60	10.5	16.5	0.735	15	
		30	8.5	16.3	0.55	16	
0.05	PIP	90	30	18.5	1.5	14	
		60	15.5	16	0.775	15	
		30	11	17	0.595	16	

Simultaneously, the output force will increase, too. The required angle and force depends on both the appropriate assistant force and the resistance force of the finger splint. Therefore, the experimental testing for the SMA-made actuator, a dynamic splint use for finger/joint rehabilitation, is carried out. In order to reach a maximal output force, the ranges of electrical voltage and circuit used for heating up the SMA-made actuator are 3.5 V and 14–16 A. Two kinds of SMA (with 50 mm and 70 mm in length) wire adopted in the study are pre-bent (with 30°, 60°, and 90° of angles) as dynamic splints for the finger/joint rehabilitation.

The experimental measurement simulating the rehabilitation of the MP and PIP tendon is shown in Fig. 10. The simulation results indicate the required forces with respect to 70 mm (MP) and 50 mm (PIP) at a preset angle of 90°.

The SMA-made actuator is heated using three kinds of electrical circuits (16 A, 15 A, and 14 A). Here, the room temperature for the SMA-made actuator is 29 °C. Fig. 11 indicates that the heating process will stop when the SMA reaches 70 °C and above with heating time of 16–19 s. Because of the thermal insulation effect in the silica-gel tube, the temperature increment of the SMA will continue within 10 s. As can be seen in figure, the peak value of the SMA's temperature will be 90 °C around. Thereafter, the temperature decrement of the SMA will start and reach 34 °C and below at the 300th second. Because current temperature (34 °C) is much less than As (42 °C, the starting transformation temperature for Austensite), there is no need to cool the SMA. For the purpose of energy and time saving, the SMA-made actuator will be reheated for the next rehabilitation at 34 °C.

3. Results and discussion

The experimental results reveal that a rehabilitation performance will be achieved when the SMA-made actuator is heated to 55 °C. The SMA-made actuator can be adjusted to meet the requirements of the assistant force and resistance force during the rehabilitation process. That is about over 20 N [30,33,34].

The bending moment can be calculated by the measured force. As indicated in Table 2, the output force will increase if the bending angle increases. On the other hand, the output force will decrease if the bending angle decreases. And, the rehabilitation time will be shorter when the electrical circuit increases. In addition, using the same 90° angle, the output forces for actuators with various lengths (50 mm and 70 mm) are 30 N and 20 N. Therefore, a shorter actuator will provide a larger output force. Similarly, the related bending moments for actuators with various finger joint (PIP and MP) are 1.5 Nm and 1.4 Nm. Moreover, two kinds of SMA-made dynamic splints (one, the fixed-type dynamic splint; and the other, the portable-type dynamic splint) have been presented.

Because the driving force is proportional to the Young's module (E), the increment of the heating temperature will result in a higher E; therefore, to manipulate a specific output force, the adjustment for the upper limit of SMA temperature is required. To accurately control the operating temperature on the SMA-made actuator, both the microcontroller and the PC-based controller in conjunction with the VB interface have been used to manipulate the electrical voltage and circuit. The thermal feedback system in conjunction with the thermocouple used for the SMA's thermal control is also established.

As indicated in Figs. 9(b) and 11, because of the insufficient cooling effect in the silica-gel tube, a ripple of the temperature that reduces the system response will occur during the cooling process. Therefore, in order to improve the drawback of the ripple effect, a more efficient cooling system embedded within the SMA actuator using forcing convection is expected in future.

Consequently, explanation and assistance provided by a physiotherapist is required during the tendon's rehabilitation process while the dynamic splint is bending and extending. For each rehabilitation stage, various resistance and assistance forces for the tendon's unidirectional training are necessary. The rehabilitation can prevent the tendon from adhesion. The SMA-made dynamic splint is adjustable when selecting the appropriate resistance and

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assistance force by tuning the electrical voltage and circuit to vary the temperature on the SMA wires.

4. Conclusions

A bidirectional shape memory alloy ($Ti_{50}Ni_{45}Cu_5$ with 1.0 mm in Φ) has been adopted as a dynamic splint for rehabilitating a finger joint. Because the driving force is tightly related to the heating temperature, the adjustment for the upper limit of SMA temperature is required. To accurately control the operating temperature on the SMA-made actuator, both the microcontroller and the PC-based controller in conjunction with the VB interface have been used to manipulate the electrical voltage, circuit, and the temperature limits. Because of the insufficient cooling effect in the silica-gel tube, a ripple effect that retards the system response will occur during the cooling process. Therefore, a more efficient cooling system embedded within the SMA actuator will be planned and expected in future.

Nevertheless, the new SMA-made dynamic splint can indeed provide rehabilitation for an injured tendon after surgery. Moreover, it can also provide sufficient force and loadings such as the assistance force and resistance force in the second and third stages, respectively. The experimental results reveal that both the SMA-made actuators (one, the fixed-type dynamic splint; and the other, the portable-type dynamic splint) work well in the rehabilitation process. They can be flexibly adjusted to meet various finger sizes. The fixed-type dynamic splint uses a PC-based controller in conjunction with a VB interface which is suitable for a clinical rehabilitation process. Moreover, the portable-type dynamic splint controlled by a microcontroller (PIC18F452) is suitable for a rehabilitation process at home.

Consequently, both the SMA-made dynamic splints have the SMA's temperature-feedback system which keeps the splint at a safe temperature. The output force derived by the SMA-made actuator developed in this study is over 22 N. The force is sufficient to be used in the rehabilitation process.

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