Evaluation of Shape Memory Alloy Wire for Applications in Hand Prosthesis

C.Y. Low*, M. A. Abu Kasim, M. F. Md Abul Mansur, R. Jaafar and A. Jaffar

Centre of Excellence for Humanoid Robotics and Bio-Sensing, Faculty of Mechanical Engineering, Universiti Teknologi MARA, Malaysia
*E-Mail: low.uitm@gmail.com

Summary: Due to advantages such as powerful, light weight, small size and low energy consumption, Shape Memory Alloys (SMAs) have been used nowadays as an actuator in hand prostheses. When current is applied, the SMA wire is heated up. A phase transformation from Martensite to Austenite takes place and the wire contracts. This paper presents the development of a test rig to access the displacement and force produced from the contraction of a type of SMA wire, i.e. Nitinol (Ni-Ti). The displacement is determined by a linear potentiometer while the force is determined by a load cell. Furthermore the impacts of varying the bias force exerted on the SMA wire and the input current passed through it are investigated. Such insight into the characteristics of SMA can be used to improve the dexterity of hand prosthesis.

Keywords: Shape Memory Alloy, Smart Material, Prosthetic Finger, Hybrid Actuator, Mechatronics.

1. Introduction

Prosthetic hands are artificial devices developed to mimic the functionality of a natural human hand. Development of a prosthetic hand is a challenge due to the high level of anthropomorphism and dexterity required. Besides a natural appearance which can be achieved by mimicking the shape, size and colour, a prosthetic hand must be capable of gripping objects and even manipulating them just like a natural hand.

Shape Memory Alloys (SMAs) refers to a group of materials which have the ability to return to a predetermined shape. This phenomenon, which is referred as the shape memory effect, is caused by a temperature dependent crystal structure [1]. SMAs display two distinct crystal structures or phases, which are martensite exits at lower temperatures and austenite exists at higher temperatures. When a SMA is in martensite form at lower temperatures, the alloy can easily be deformed into any shape and when the SMA is heated it goes through transformation from martensite to austenite [2]. However, when the SMA is heated and then cooled, the phase of the SMA will not straight away change from austenite to martensite without any external load or bias force, it will change to a structure called twinned martensite. Transformation temperature is dependent on the ratios of the metals in the alloy. This phenomenon can be harnessed to produce a unique and powerful actuator.

The actuators for hand prostheses must be installed within a limited space and be able to produce a stroke large enough to enable meaningful motion of the fingers for grasping. As such, the importance of a small and effective actuation system prevails. In the last few years, SMAs have attracted the attention of researchers in the field of robotic prostheses. Some of the well known SMA-actuated prosthetic hands include the Hitachi Hand [3], the Rutgers Hand [4] and the SBC Hand [5].

Shape Memory Alloy (SMA) has been identified as an ideal candidate to actuate the finger joints due to its small size, high force to weight ratio and operational similarity with human muscles. The unique behaviour of SMA, i.e. its ability to produce a large actuation force and displacement when heated by direct current, made the SMA more superior in comparison to the other conventional actuators such as electric motors, tendon wires, pneumatic systems and hydraulic systems [6]. Besides that, the SMA actuator is simple because it does not require any lubrication as in hydraulic and pneumatic systems. The other advantages of SMA include silent operation, low cost, high reliability and simple control by electrical current [7].

This paper presents the development of a test rig designed to access the contraction displacement and contraction force produced by SMA wires. The test rig is capable of testing the bias force exerted onto the SMA wire. Bias force is the level of stress one uses to reset the wire, or to stretch it in its low temperature phase [8]. Without the presence of bias force, the wire will not return fully to its original length. Besides that, it helps to accelerate the rate of cooling of SMA wires.

2. Experimental Setup

The Flexinol Ni-Ti wire was chosen because of the ready-to-use characteristic compared to the ordinary Nitinol such as Cu-Zn-Al and Cu-Al-Ni. The Ni-Ti can be easily heated by direct current and its contraction ranges between 3%-4% and approximately store up to 110% depending on the arrangement of the wire [8]. To evaluate the effectiveness of SMA wires as actuators, a test rig as shown in Figure 1 has been constructed. A SMA wire with length of 115mm and diameter of 0.508mm is connected in series to a normal bias spring with a spring constant of 11.92N/mm. The SMA wire is fixed to the spring at one end and to a load cell at the other end. A linear potentiometer from *K. Fader* is placed parallel to the SMA wire to measure the contraction displacement produced by the wire. The force produced by the SMA wire is measured by a load cell from *Interface*. Both measurement data for the displacement and force are sent to the data logger to be evaluated.

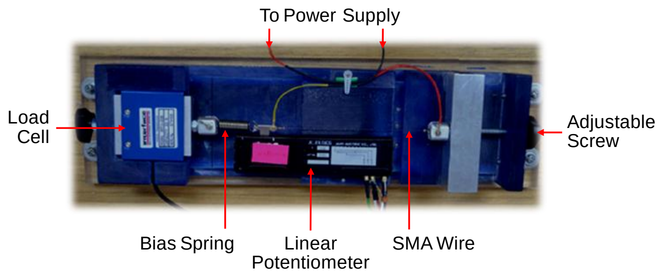

Figure 1. Experimental setup to testing a SMA.

The purpose of this experiment is to identify the characteristic and behavior of SMA wire and to obtain the range of parameters to be used later as actuator in a prosthetic hand. The first focus is to study the contraction displacement produced by the SMA wire and its ability to return back to the original length when the wire is exerted with varying bias force. The second focus is to study the contraction displacement and contraction force subject to varying input current. The SMA wire is heated by direct current supplied by power supply. The experiments were conducted at room temperature.

3. Results

3.1. Impact of Bias Force

A bias force will have substantial impact on the characteristics of the SMA wire during the heating process and the cooling process. Figure 2 shows the behaviour of the SMA wire when it is heated up using a direct current of 3.2A and 2.8V for 15 seconds, and then cools down naturally by cutting off the power supply. In order to investigate the impact of bias spring, two experimental setups have been used. In the first setup, no bias force was applied to the SMA wire. In the second setup, a bias force ranging from 11N to 13N was applied to the SMA wire by means of a normal bias spring.

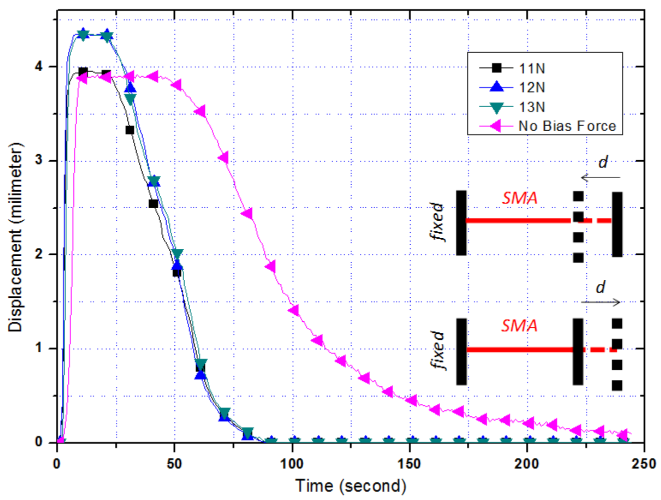

Figure 2. Contraction and relaxation of SMA wire subjected to varying bias force.

When the SMA wire heats up, it can be observed that more contraction displacement can be obtained when a bias force is applied to the wire. Increasing the bias force from 11N to 12N, the contraction displacement increases from 3.4% to 3.8%. Nevertheless, increasing the bias force further to 13N, the contraction displacement remains at 3.8%. It can be concluded that, up to a certain point, the higher the bias force the higher the contraction displacement. It can be also observed that the bias force can improve the rate of contraction.

When the SMA wire cools down, it can be observed that a higher cooling rate can be obtained if a bias load is applied to the SMA wire. Besides that, it can be observed that the SMA wire did not return back to its original length completely without a bias force. It can be concluded that the bias force helps to pull the SMA wire back to its original length and reduces the required time during the cooling process. Precaution should be taken as too large a bias force will result in damage to the wire that causes permanent elongation. To improve the cooling rate, additional methods of cooling using forced air, heat sink, increased stress and liquid coolant can be attempted [8].

3.2. Impact of Input Current

Since the SMA wire is thermally activated, its characteristic is influenced by the input current. The SMA wire is exerted with a 12N bias force, and heated up using a direct current of 2.4A to 3.4A and 2.8V for 15 seconds. The displacement and the force produced as a result of the contraction of the wire during the heating process are measured and analyzed as shown in Figure 3.

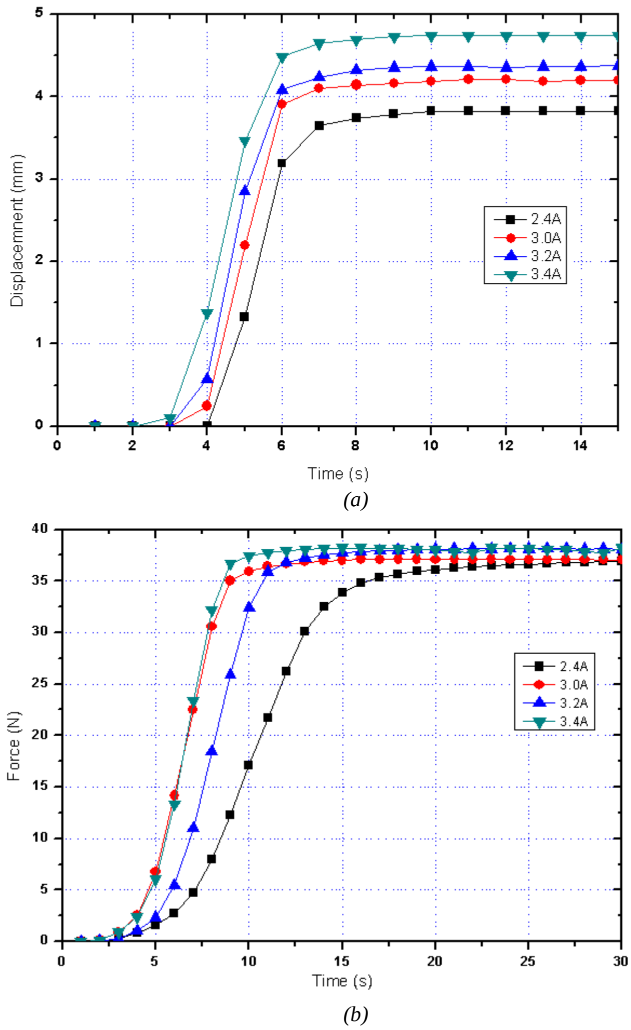

Figure 3. Displacement *(a)* and force *(b)* produced by a SMA wire during contraction subjected to varying input current.

It can be observed that by increasing the input current from 2.4A to 3.4A, the contraction displacement increases from 3.3% to 4.1% as shown in Figure 3(a) while the contraction force increases from 36.9N to 38.2N as shown in Figure 3(b). From the measurement result, it can be seen that the time taken to reach the maximum force and displacement decreases as the energizing current increases from 2.4A to 3.4A. It can be concluded that the higher the amperage, the faster the wire contracts as the rate of contraction is influenced by the rate of heating.

4. Application in Prosthetic Hand

The SMA wire will be integrated into a hybrid actuation mechanism for a hand prosthesis. The internal structure of the prosthetic finger is shown in Figure 4. A miniature DC motor and a SMA wire are used to actuate the MCP joint and the PIP joint independently. The DIP joint rotates in correspondence to the PIP joint rotation by means of crank linkages. The MCP joint can be rotated without forcing the PIP joint to rotate along, and vice versa.

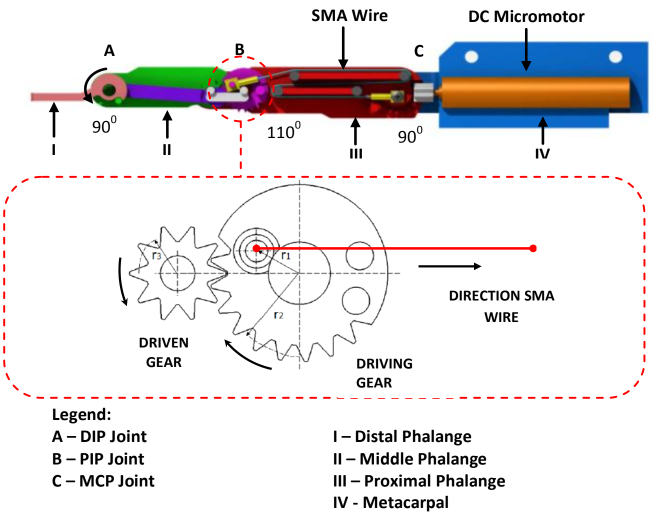

Figure 4. Internal structure of the hybrid-actuated finger prosthesis.

The MCP joint is actuated by a Faulhaber DC micromotor and thus providing a precise and accurate control at that joint. Combination of a spur gear and a crown gear enables this joint to transmit torque from the motor to the proximal phalange at a right angle with a gear ratio of 5:1. Hence, the generated torque is enhanced. A stopper is designed at the positions of 0° and 90° to avoid the proximal phalange to rotate beyond this range. A graphical user interface (GUI) has been developed using Visual Basic for the control of the angular displacement of the micro-motor. Three modes of operation are possible, i.e. fully open posture (0°), partially closed posture (45°) and fully closed posture (90°).

The PIP joint is actuated by a SMA wire. When the SMA wire is heated, the middle phalange rotates inwards. The SMA wire is used mainly due to the limitation of space here. Since the contraction of the wire is limited, a direct actuation approach will not be able to produce a 110° rotation at the PIP joint. Therefore, a gear set with a ratio of 1:2 is used to amplify the degree of rotation. By using a gear system as shown in Figure 4, the SMA is able to produce a 110° rotation by a contraction of 4% from the original length of 115mm. The energizing current for the SMA wire is controlled using Pulse-Width Modulation (PWM) [9]. Two modes of operation are possible, i.e. fully open posture (0°) and fully closed posture (110°).

The DIP joint consists of a driven pulley, a linkage and a connecting bar. The driven pulley is the distal phalange itself. As the middle phalange rotates, the connecting bar will push the distal phalange to rotate along. A torsion of spring is attached at this joint which is used to reverse the motion when no current is supplied through the SMA wire.

5. Conclusion

SMA wires exhibit great potential for the actuation of finger joints in hand prosthesis. Based on the experimental studies, it is observed that the displacement and contraction force that can be produced by a SMA wire is directly dependent on the bias force exerted on the wire and the input current passed through it during the heating process. From the measurement, the optimal value of bias force is 12N and the optimal value of input current is 3.4A. Nevertheless, such experiments have to be repeated for SMA wires of different lengths and diameters. Furthermore, a forced cooling method based on heat sink will be developed to improve the cooling time.

Acknowledgements

This project is funded by the Ministry of Higher Education Malaysia under the grant number *600-RMI/ST/FRGS 5/3/Fst (256/2010)* and *600-RMI/ERGS 5/3 (23/2011)*.

References

[1] Ti-Ni Aerospace , Inc. “Shape Memory Alloy” 2235 Polvorosa Ave, San Leandro, LA 94577.
[2] Soares, A. B., 1997, Shape Memory Alloy Actuators for Upper Limb Prostheses. vol. Degree of Doctor of Philosophy: University of Edinburgh.
[3] Yoshiyuki et al., N., 1984, Hitashi’s Robot Hand, Robotics Age 6.
[4] De Laurentis, Kathryn J., Mavroidis, C., 2002, Mechanical design of a shape memory alloy actuated prosthetic hand, Technology and Health Care 10:91–106.
[5] Kyu-Jin Cho, Rosmarin, J., Asada, H., 2007, SBC Hand: A Lightweight Robotic Hand with an SMA Actuator Array implementing C-segmentation, Robotics and Automation, IEEE International Conference:921-926.
[6] Pfeiffer, K. D. Charles, 1999, Constantinos Mavroidis, Shape Memory Alloy Actuated Robotic Prostheses: Initial Experiments, Robotics and Automation.
[7] Bundhoo, V., Haslam, E., Birch, B., Park, E. J., 2009, A shape memory alloy based tendon-drive actuation system for biomimetic artificial fingers Part 1: Design and Evaluation, Cambridge Journals.
[8] DYNALLOY, Inc. Maker of Dynamic Alloys, Technical Characteristics of Flexional.
[9] Ma, N., Song, G., 2003, Control of shape memory alloy actuator using pulse width modulation, Smart Materials and Structures, IOP Publishing, 12/5:712-719.