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Finger-Like Manipulator Driven by Antagonistic Nickel-Titanium Shape Memory Alloy Actuators

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***Abstract*— Shape memory alloy (SMA) actuators generally have a fast response time when heated. However, the return stroke during cooling can be slow and has been a hindrance to the application of SMA actuators in different areas such as robotic hands. Thus, a novel finger-like antagonistic SMA actuator design is presented in this paper. By using different thermal shape setting processes, one SMA actuator was designed to take a curved shape when heated. This actuator was antagonistically coupled to a different actuator that took a straight shape when heated. Thus, alternately heating each actuator caused the finger-like manipulator to flex and extend rapidly. A comparison study was performed between the novel antagonistic design and a single actuator which showed that the both designs applied approximately the same force with the same velocity when flexing. However, the antagonistic design was able to extend, or open, more rapidly with statistical significance. This was demonstrated for 1.5mm, 1.9mm, and 3.0mm SMA actuator diameters.**

Keywords—nickel-titanium; robotic finger; shape memory alloys; SMA actuator; antagonastic SMA manipulator

I. Introduction

Due to their light weight, SMA actuators offer tremendous advantages over traditional motors [1, 2]. SMA has been used in a variety of robotics applications such as with micromanipulators [3], pumps [4], bioinspired inchworms [5], and biomimetic fish [6]. SMA actuators have been incorporated into robotic hands as well [7, 8]. Several groups have used SMA wires attached across the joints of the fingers [9]. In this manner, heating the SMA wire results in flexion or extension of that particular joint [10]. This has also been done with tendon drive systems using SMA wires in series with linear springs [11] or through segmented binary control [12]. SMA actuators have also been used in conjunction with DC motors for hybrid actuation of an artificial finger [13] and a surgical manipulator [14]. Other groups have investigated the use of SMA springs to actuate artificial grippers [15].

During the heating phase, SMA actuators typically have a fast response time [16]. However, one problem that has not been resolved with the application of SMA to robotic hands is that SMA requires a lengthy amount of time to cool down and return to its initial state [9, 17], even with forced air convection [15]. This low bandwidth limits the utility of SMA as an actuator in several areas, such as with prosthetic limbs [1, 18].

We have overcome this drawback by taking a novel bioinspired approach to design antagonistic SMA actuators that function similar to extensor and flexor muscles for human fingers [19]. The process involves using two SMA wire actuators in parallel. Using a mold, one SMA actuator was thermally shape set so that it took a curved shape when Joule heated. The other SMA actuator took a straight configuration when heated. These two actuators were mechanically coupled together at the end points so that alternately heating each SMA actuator caused the artificial finger to flex and extend (Fig. 1) similar to how antagonistic muscle groups flex and extend human fingers. The result is a finger-like manipulator that can more rapidly open and close, which opens the possibility for many different robotic applications. A general background on shape memory effect mechanism and further details can be found in the reference [20]. In this paper, the performance of the antagonistically connected NiTi SMA wires was experimentally compared to a single SMA wire to investigate the feasibility of increasing the system bandwidth with the new design.

II. Materials and Methods

A. SMA Actuator Material Properties

To investigate the antagonistic actuation behavior, three NiTi SMA wire actuators were used with diameters (D) of 1.5, 1.9, and 3.0mm, all with lengths of 85mm (Fig. 2). A length of 85mm was chosen as this is well within the range of average human index finger lengths [21]. The 1.5mm and 1.9mm diameter wires were obtained from NDC (Fremont, CA) while the 3.0mm wire was purchased from Memry (Germany). The material properties for each of these wires are listed in Table 1. The phase transformation temperatures for the martensite and austenite start (M_s, A_s) and finish (M_f, M_s) were respectively measured with differential scanning calorimetry (DSC) using a TA Q200 (TA Instruments, Inc) with a heating/cooling rate of 10°C/min. The resistance of the NiTi wires is listed by the manufacturers as 76 μΩ-cm in martensite phase, with 49.7% composition by weight of nickel.

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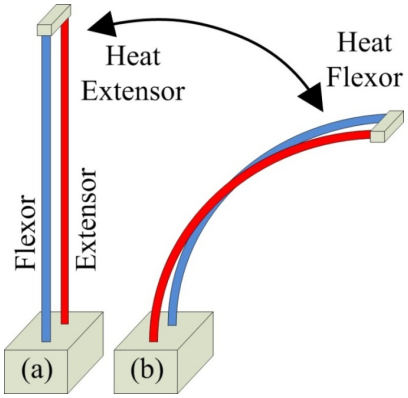

Fig. 1. The schematic of the finger-like manipulator using antagonistic NiTi SMA wires. (a) The manipulator extends, or opens when the extensor is heated. (b) The manipulator closes, or flexes when the flexor actuator is heated. The red and blue indicate hot and cold temperatures.

TABLE I.

Material properties of SMA actuators	**SMA wire diameter**		
	1.5mm	***1.9mm***	***3.0mm***
Surface finish	Mech.polish	Chemically pickled	Chemically pickled
M_f (°C)	32.45	39.22	23.42
M_s (°C)	58.83	55.58	43.51
A_s (°C)	82.64	52.04	51.18
A_f (°C)	96.72	51.15	81.35

B. Antagonistic Actuator Design

An aluminum mold was designed to shape set the NiTi SMA wires: a ring with a 30mm inner diameter was machined into an aluminum plate. The depth of the channel was 5mm while its width was 4mm. SMA wires of each of the three diameters were sequentially fit into this channel and shape set to impart a curved shape. The straight SMA wires were also shape set using a straight copper tube; these SMA wires were placed within the straight copper tube and held in place with set screws. Using a 48000 Furnace (Barnstead/Thermolyne), the shape setting process of the NiTi wire samples was performed at 550°C for 5 minutes. After heat treating the wires, they were water quenched. To stabilize the obtained stroke from the wires, ten thermomechanical training cycles were conducted for each SMA wire before starting the actuation experiments.

SMA actuators are often heated electrically by Joule heating [4]. Since the electrical resistivity of the SMA wires is approximately 76 μΩ-cm in martensitic phase, they can be quickly heated by electric current. A 165X5 transformer (Hammond Manufacturing, Cheektowaga, New York) was used to Joule heat the SMA actuators.

To develop an experimental platform to evaluate the different SMA actuators, a rectangular block (6.8cm x 6.8cm x 2.6cm) of ABS polymer was used as a base (Fig. 3). A drill press was used to make four parallel cylindrical holes centered along the length of the ABS base. A copper tube (6.5mm OD x 4.5mm ID x 6.8cm long) was press fit into each of the two inner cylindrical holes within the polymer base. A set screw was inserted into each end of the copper tubes through the ABS polymer base, one to hold the SMA wire in place on one side and another to secure 10 gauge wire on the other side. The outer two cylindrical holes in the ABS base were used to run 10 gauge wire through to connect to the distal ends of the SMA wires that protruded out of the polymer base.

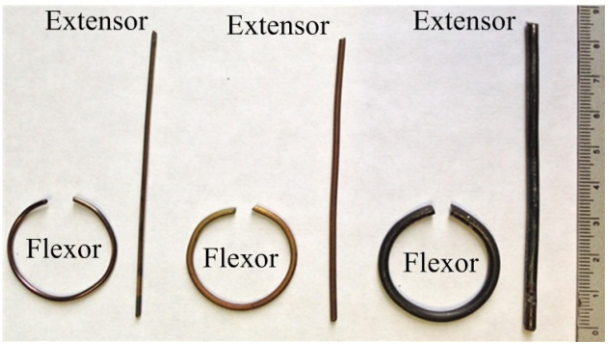

Fig. 2. The flexor and extensor SMA wires for the 1.5mm, 1.9mm, and 3.0mm diameters from left to right, respectively.

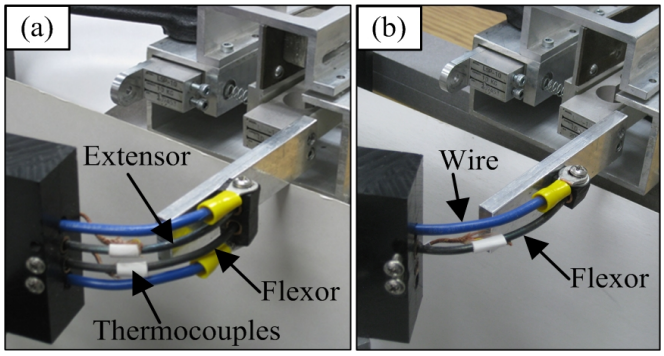

Fig. 3. (a) The flexor and extensor are mounted in grounded copper tubes that are within the black ABS polymer base. Each stranded blue 10 gauge electrical wire is connected to the transformer on one side and its respective SMA actuator on the other side via the ring connector to enable current flow through the SMA actuators. When the flexor is heated, the manipulator displaces the manipulandum. When the extensor is heated, the manipulator returns to its initial position. The temperature of each actuator is measured with a K-type thermocouple. (b) The same is true for the single SMA actuator experiments, except there is no extensor actuator to enable a quick return stroke as with the antagonistic design.

To that end, a small rectangular connector (2.2cm x 1cm x 1cm) was made out of ABS polymer for the distal ends of the SMA actuators as well. This connector served to mechanically couple both SMA wires together on one side; additionally, it functioned as an electrical connector to enable current flow through each individual SMA actuator. Within this connector, two holes were made for similar copper tubes to hold the SMA actuators in place. Holes were machined in the sides of the connector to allow set screws to constrain the SMA actuators. The 10 gauge electrical wires from the transformer were connected to these set screws via ring terminals to enable current flow through each SMA wire. Both SMA actuators

were placed in series with a two-port switch so that either actuator could be Joule heated by the transformer.

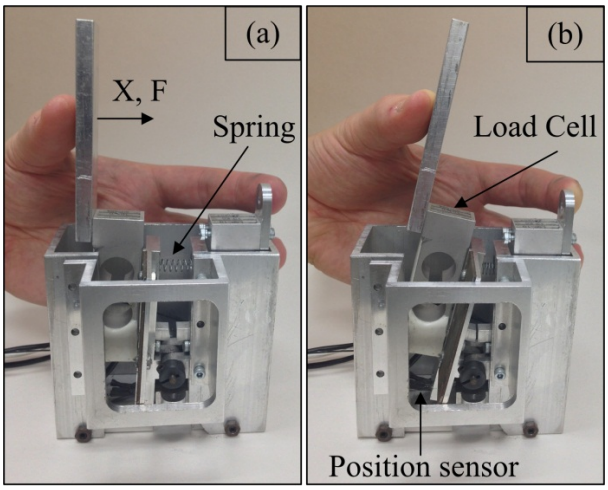

Fig. 4. (a) The manipulandum has a slot wherein a compression spring is placed to oppose the motion (X) and applied normal force (F). (b) The position is measured by a Hall effect sensor at the base while the applied force is measured by a load cell.

To provide a comparison basis, a single actuator was also evaluated (Fig. 3b). In the single actuator case, the curved SMA actuator was used without the straight SMA actuator.

C. Experimental Protocol

A manipulandum (which has been described elsewhere [19]) was used in this paper to measure the force and displacement of the artificial finger (Fig. 4). Briefly, there is a slot wherein a compression spring was placed and an A1321 Hall effect sensor (Allegro Micro Systems Inc., Worcester, USA) was mounted at the base of the manipulandum to indicate the displacement (X) of the end effector. A LSP-10 load cell (Transducer Techniques, Temecula, USA) was used to measure the force (F) applied by the artificial finger.

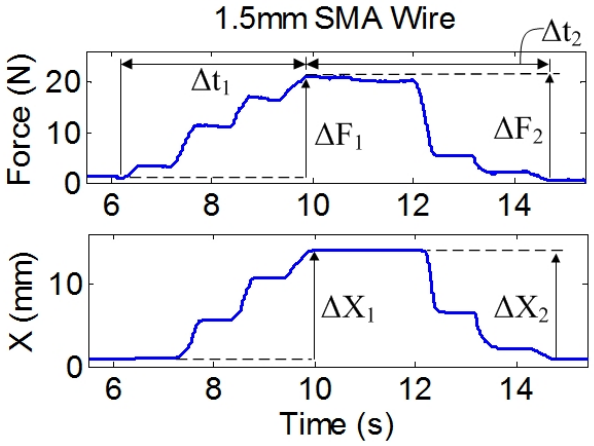

Fig. 5. Force and position response of 1.5mm NiTi SMA with the antagonistic configuration as shown in Fig. 3a.

A comparison study was performed in this paper between two cases: antagonistic (Fig. 3a) and water cooled, with a single SMA actuator (Fig. 3b). All three SMA wire diameters (Fig. 2) were evaluated in both of these cases. During the antagonistic experiments, the manipulandum and ABS polymer base with the SMA wires were clamped in place so that the polymer connector was lightly in contact with the manipulandum (Fig. 3a). K-type thermocouples (Omega, Stamford, USA) were affixed to each SMA wire to measure the temperature of the flexor (T_F) and the extensor (T_E) actuators. Next, the flexor SMA wire was Joule heated until the maximum possible force was applied. Then, the extensor SMA wire was heated to cause the artificial finger to return to its initial position as quickly as possible. This procedure was performed ten times with each of the three diameters of SMA wire. This resulted in characteristic loading and unloading cycles as shown in Fig. 5.

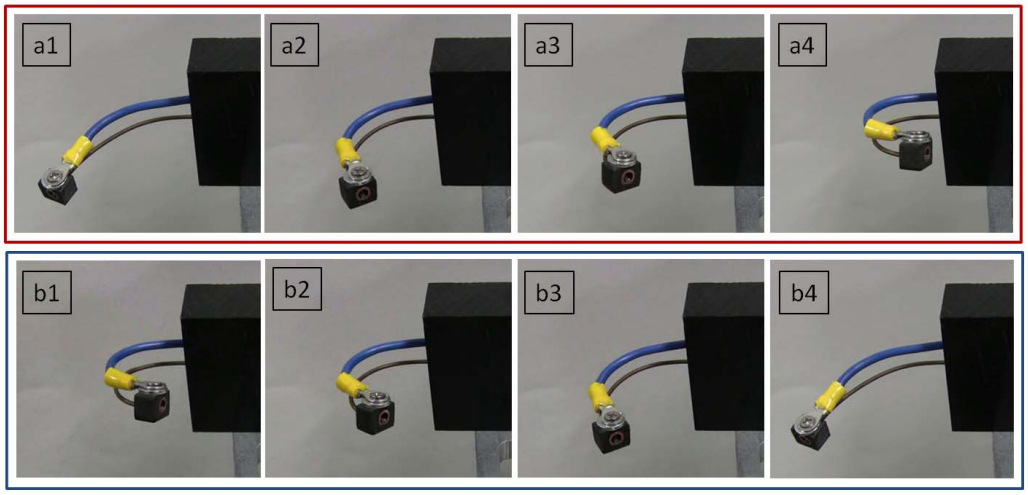

Fig. 6. Photo sequence of the 1.5mm NiTi SMA actuator. (a) When the actuator was Joule heated, the manipulator flexed. (b) The actuator slowly extended as it was allowed to cool.

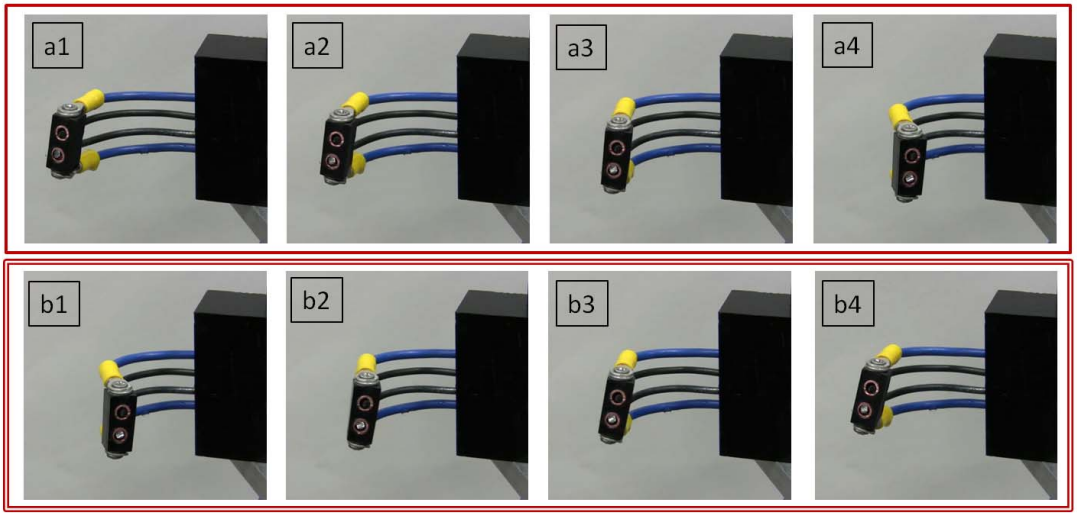

Fig. 7. Photo sequence of the 3.0mm NiTi SMA actuators with the antagonistic configureation. (a) The finger-like manipulator flexed as the flexor was Joule heated. (b) The manipulator rapidly extended when the extensor was heated.

From these recorded data sets, characteristic traits were identified during the flexing and extending portions of the experiments. Δt_1, ΔF_1, and ΔX_1 were the amount of time, force, and displacement that occurred while the finger flexed, respectively. Δt_2, ΔF_2, and ΔX_2 were the amount of time, force, and position that occurred while the finger extended. The average speeds during flexion ($V_1=\Delta X_1/\Delta t_1$) and extension ($V_2=\Delta X_2/\Delta t_2$) were also calculated. These parameters were used as performance metrics to compare the antagonistic and water cooled methods.

Similar experiments were performed with a single wire for flexion (Fig. 3b). Our initial experiments in this configuration with a single wire to squeeze the manipulandum were performed by Joule heating the flexor; when environmental convection was permitted to enable the wire to return to its initial position, each grasp cycle required approximately 4 minutes to complete due to the lengthy cooling time during the return stroke. This problem has been noted by many other research groups [9, 15, 17]. Thus, we opted to speed up the return stroke by applying 23°C water to cool the SMA during the single wire experiments (Fig. 3b). With all three of the SMA wire diameters, ten repetitions of squeezing and releasing the manipulandum were performed by Joule heating the flexor and then immediately water cooling the wire. By lightly applying water to the SMA actuators with a brush, the return stroke speed was increased substantially to enable a more competitive comparison with the antagonistic configuration which was not water cooled (Fig. 3a). All data were recorded with a 1kHz sample frequency using a PCI-6229 (National Instruments) card interfaced with MATLAB/Simulink (The MathWorks, Natick, USA) via the real time Windows target kernel.

A two way analysis of variance (ANOVA) was performed on the performance metrics shown in Fig. 6 to determine if there was a statistically significant difference between the antagonistic (Fig. 3a) and water-cooled single wire (Fig. 3b) configurations. Specifically, ΔF_1, ΔF_2, V_1, and V_2 were compared for all three wire diameters for the antagonistic and single wire configurations. A p value ≤ 0.01 was assumed for statistical significance.

III. RESULTS

Photo sequences of the heating and cooling of the 1.5mm diameter single actuator to flex and extend are depicted in Fig. 6(a1-a4) and Fig. 6(b1-b4) respectively. Corresponding photo sequences with the antagonistic design with 3.0mm diameter are shown in Fig. 7(a1-a4) when the flexor was heated and Fig. 7(b1-b4) when the extensor was heated; both of these figures show the full range of motion without any external applied load.

When the single wire was in contact with the manipulandum as in Fig. 3b, it is clear that the flexing stroke occurred quickly, but the extension stroke required a significant amount of time due to the lengthy cooling process (Fig. 8). This was substantially improved with the antagonistic design, as can be seen from sample data with the 1.5mm and

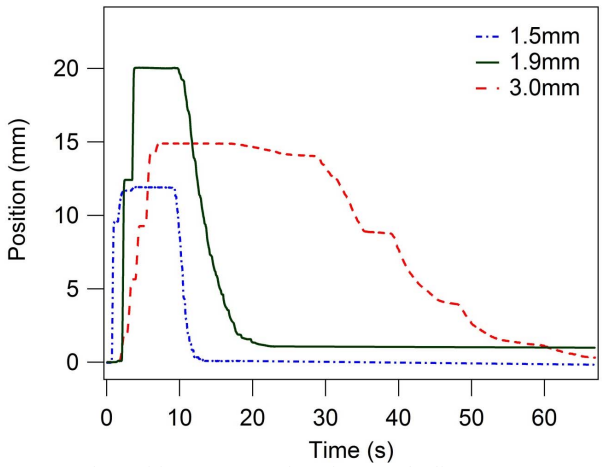

Fig. 8. Sample position response data from each diameter SMA actuator during the single wire experiments. The flexion stroke is rapid while the extension stroke is lengthy due to the slow cooling process.

1.9mm diameters when compressing the manipulandum (Fig. 5 and Fig. 9). As the flexor actuator was initially heated, T_F began to increase (Fig. 9b), prompting the finger-like manipulator to flex, resulting in an increased force and position (Fig. 9a). Then, the extensor actuator was heated and T_E (Fig. 9b) began to increase resulting in the return stroke of the manipulator and a reduction of the force and position to the same levels as the start of the experiment (Fig. 9a).

The amount of change in force exerted during the flexion (ΔF_1) and extension (ΔF_2) strokes was comparable between the single and antagonistic actuators (Fig. 10). On average, the 3.0mm actuators were able to exert the greatest forces while the 1.5mm actuators exerted the least force. There was no statistically significant difference between the amount of force exerted by the single and antagonistic actuators ($p > 0.01$); however, the diameter of the SMA actuator significantly impacted the applied force with both the single and antagonistic actuators ($p < 0.01$).

With respect to the average velocity during the flexion stroke, the 1.9mm diameter SMA actuator proved fastest and the 3.0mm diameter was slowest with both single and antagonistic actuators (Fig. 11). There was no statistically significant difference between the single and antagonistic actuators with respect to the speed during the flexion stroke ($p > 0.01$); however, the influence of the actuator diameter was again significant in each case ($p < 0.01$). This is in contrast to the average velocity during the extension stroke where the antagonistic actuators were statistically faster than the single actuator ($p < 0.01$) with each wire diameter ($p < 0.01$). All interaction effects from the two way ANOVAs were not statistically significant in every test for the force and velocity.

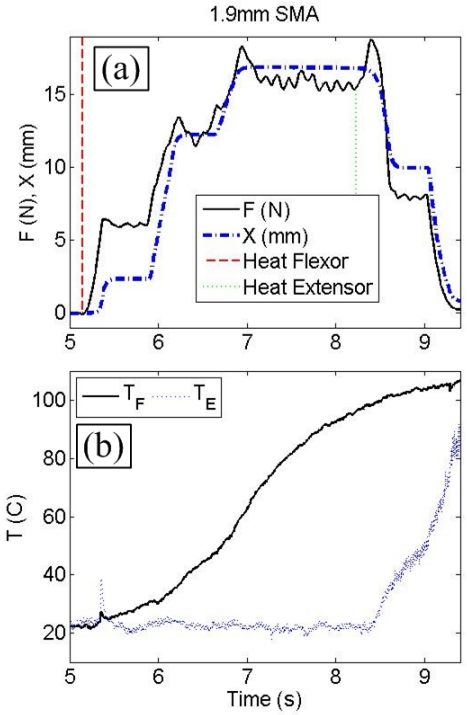

Fig. 9. Sample data from the 1.9mm diameter antagonistic SMA configuration. The force and position increased (a) as the flexor muscle was heated, indicated by the rise in the flexor temperature T_F, (b). Then, the position and force decreased as the extensor actuator was heated as is indicated by the increase in the extensor temperature, T_E.

IV. DISCUSSSION

During the flexion stroke, the 1.9mm wires were fastest with the single and antagonistic designs. The likely explanation for this is that the 1.9mm actuator had substantially lower austenite and martensite phase transition temperatures than the 1.5mm diameter actuators, as shown by in Table 1. The functional properties, especially phase transformation temperature of NiTi SMA wires, are strongly sensitive to the thermo-mechanical processing history. The surface finish is also different between the two actuators, but this is less likely a significant factor in the difference in actuation speeds.

As expected, the SMA actuators were able to apply greater forces as the actuator diameter was increased. While no statistically significant difference emerged in the amount of force that was applied between the single and antagonistic actuators (Fig. 10), the single actuators were able to apply slightly greater forces on average. This is due to the extra load of the extensor actuator that was driven by the flexor with the antagonistic design. The trade-off is that the average velocity during the extension portion was substantially faster with the antagonistic design with statistical significance. Based on the results in this paper, the 1.9mm antagonistic actuator design provided the best overall performance in terms of force, closing, and opening speeds.

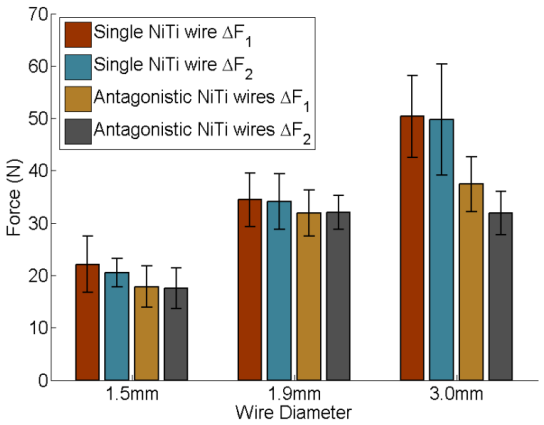

Fig. 10. Force response of single and antagonistic NiTi SMA actuators during the flexion (ΔF_1) and extension (ΔF_2) strokes.

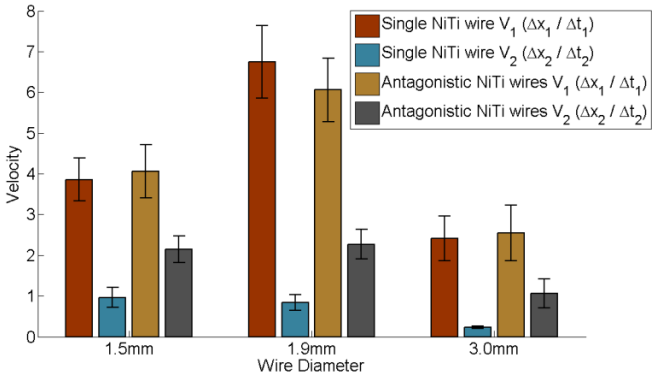

Fig. 11. The average velocity of the single and antagonistic NiTi SMA actuators. The average velocity during the extension strokes (ΔV_2) is significantly faster with the antagonistic design with each diameter.

The development of this novel antagonistic SMA actuation concept could open the range of applications of SMA actuators to several different areas such as prosthetic hands, where the slow return stroke of other SMA actuator designs has been a hindrance in the past. Since the mass of prosthetic hands is an important design consideration [22], the low weight profile of the antagonistic design would be a desirable feature since the mass of prosthetic hands has been identified as a potential area of improvement by amputees. This antagonistic actuator design could also offer a great reduction in the size and mass of research-based artificial hands. The precision of control and the power requirements may be more demanding with the SMA design, however. Another excellent application for this research would be in underwater grasping [23] for exploratory, salvage, or rescue purposes. When immersed undersea, the SMA actuators would have a natural cooling medium to enable a speedy return stroke. However, the antagonistic design would still provide a faster return stroke and a capacity to apply forces in both directions, something that would not be controllable with the single actuator design.

V. CONCLUSION

In response to the low system bandwidth of SMA actuators, a novel finger-like manipulator has been presented that is made from two antagonistically connected SMA actuators. One SMA actuator was thermally shape-set to take a curved shape when heated while the other actuator took a straight shape when heated. Heating these actuators alternately produced rapid closing and opening motions. In comparison to a single SMA actuator, the antagonistic design had a statistically faster system response with three different SMA actuator diameters while still applying approximately the same level of force. The development of a current control circuit for closed loop position control with a nonlinear error manifold is still in progress. Position feedback will be used along with a flexible tactile sensor for force feedback. Additionally, a human-inspired thermomechanical shape setting process to enable anthropomorphic grasping will be developed. The future work for this research is to develop a molding and manufacturing process to incorporate these SMA actuators and directly printed force sensors [22] within a cosmetic finger.

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