A Bio-Inspired Electro-Active Velcro Mechanism Using Shape Memory Alloy for Wearable and Stiffness Controllable Layers

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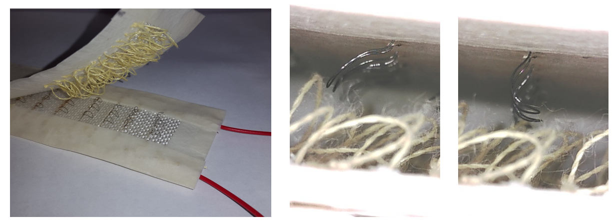
***Abstract*— Smart attachment mechanisms are believed to contribute significantly in stiffness control of soft robots. This paper presents a working prototype of an active Velcro based stiffness controllable fastening mechanism inspired from micro active hooks found in some species of plants and animals. In contrast to conventional passive Velcro, this active Velcro mechanism can vary the stiffness level of its hooks to adapt to external forces and to maintain the structure of its supported layer. The active hooks are fabricated using Shape Memory Alloy (SMA) wires which can be actuated using Lenz-Joule heating technique via thermo-electric manipulation. In this paper, we show experimental results for the effects of active SMA Velcro temperature, density and number on the attachment resisting force profile in dynamic displacement. We aim to provide new insights into the novel design approach of using active hook systems to support future implementation of active velcro mechanisms for fabrication of wearable stiffness controllable thin layers.**

I. INTRODUCTION

There is an increasing interest in different mechanisms to control the stiffness of soft robots for safe robot-humans applications. This is due to the fact that the texture and flexibility of soft robots complies perfectly with biological properties. However, one of the most noticeable challenges is the difficulty to maintain and control the stiffness level of the robot soft body [1]. Achieving a large stiffness range is a major challenge faced by soft robots. Recently, the concept of soft body jamming in the form of granular jamming [2], layer jamming [3], and scale jamming [4] is proposed where stiffness is modulated by altering the friction force in-between the media surfaces through changing the normal jamming pressure. However, granular and scale jamming are bulky, layer jamming is less deformable and weaker, and the current jamming pressure control mechanisms (air vacuum [2][3] and tendon tension [4]) limit the possibility of local and directional stiffness modulation. Hence, in order to combine the advantages of the thinness of the layer jamming with the strength of the granular jamming, this research proposes the novel approach of using active Velcro mechanism to tune the frictional interlocking of the layers



(a) (b) (c)

Fig. 1. Implementation of electro-active Velcro attachment mechanism on a deformable thin layer (a). The hooks' non-active (b) and active (c) state.

(Fig. 1). Using our new approach, we overcome the limitation of the conventional jamming mechanisms and it is easy to design and achieve regional and directional stiffness control.

Biological creatures establish fastening mechanism with different morphology and for various functions [5]. By taking inspiration from sticking burr, Velvet Crochet (Velcro) fastening mechanism was invented by George de Mestral in 1952 [6]. Since then, Velcro has become one of the most well-known releasable fasteners and different types of similar attachment mechanisms have been observed in plant species [5], [7], animals (Arboreal Ant) [8], (Leopard Gecko) [9], and some micro-organisms [10]. In plants for instance, attachment technique is utilized to constantly stipulate to an object for increasing endurance against external disturbances such as strong wind or water flow.

Conventional Velcro hook is not easily deformable and requires strong external forces to release [11], hence cannot be used for shape changing structures. Active hook structure found in some species of plants and animals can be mimicked to design flexible and controllable velcro mechanisms. With the recent progress in material science, Shape Memory Materials (SMMs), such as Shape Memory Alloy (SMA) and Shape Memory Polimer (SMP), have been mass-produced and widely implemented in robotics, biomedical engineering, aerospace, and automotive research. [12]. The capability of memorizing their original shape, SMMs have been used to fabricate active hook mechanism for active fastening [13] and even planar manipulation [14]. In a temperature lower than the material transient temperature, SMA has the martensite molecular structure and is easily deformable. While heated, SMAs regain their programmed shape due to transition to the austenite molecular structure. The power of this transition can be harnessed to be used for actuation [15] and sensing [16] applications.

In wearable robotics, the stiffness variation requires to be

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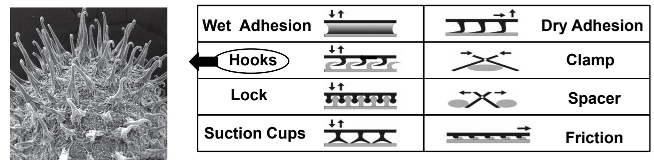
TABLE I
DIFFERENT SMA WIRES USED IN THE EXPERIMENTS

Diameter	Transition Temp	Resistance (Ω/m^3)
0.010 inch (0.25 mm)	above 80 °C	18.5
0.006 inch (0.15 mm)	above 45 °C	55
0.004 inch (0.10 mm)	70 °C to 80 °C	150



(a) (b)

Fig. 2. Bio-Inspired Active Hook Mechanisms in (a) micro plants [21] and (b) morphology of biological attachment found in some species of plants and animals [5]

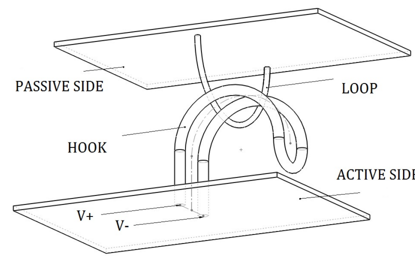


Fig. 3. An active double SMA wire hook-loop Velcro mechanism

adjusted continuously depending on the interacting environment to provide a tender physical interplay while maintaining the body stability. Various applications of this mechanism can be seen in medical robotics, such as soft robots in Minimally Invasive Surgery (MIS) [17], medical palpation process [18], body rehabilitation technology [19], and many other relevant practices. Stiffness controllable devices are believed to be the robotics' future demanding technology as it can fulfill the requirements of safety in safe human-robot and robot-environment interactions [20].

To achieve wearable stiffness variable layers, in this research we present a novel deformable multi-layer fabric with inter-layer stiffness controllable fastening mechanism based on active velcro inspired from micro active hooks found in plants and animals. This active Velcro mechanism is capable of adapting to external forces by varying its hooks' stiffness to maintain the structure of the supporting layers. This research aims to provide new insights into the design of active Velcro hooks for fabrication of stiffness controllable and wearable thin layers. To this end, the active attachment mechanism inspiration and design is presented in section II. A set of experiments are designed and carried out to investigate the characteristics and performance of the single and multiple hooks in section III. Then, the effect of different density and arrangement of the hooks and loops on the static load bearing capacity and dynamic response of the layers against shear forces are investigated experimentally and a berief discussion on the results are presented. Finally our plan and suggestions for the future works are presented in section IV followed by the research conclusion in section V.

II. BIO-INSPIRED DESIGN AND FABRICATION

Active attachment mechanism found in many species of plants and animals as presented in Fig. 2a [21] can be mimicked for conceptual design of stiffness controllable thin layers based on electro-active Velcros mechanisms. Biological fastening mechanisms can be categorized into several groups according to their morphology, such as (1) hooks, (2) lock or snap, (3) clamp, (4) spacer or expansion anchor, (5) suction, and (6) dry adhesion [5]. Natural species utilize the hook morphology for mechanical interlocking and biological frictional systems. Mechanical interlocking is quite common in parasitic plants and animals, where the function is to attach to the surface of the host body. The hook mechanism is usually sharp, small, and dispersed along the surface. Frictional systems using hook are found in the probabilistic fastener mechanisms for maintaining the structure of the species' outer body [5]. Inspired by these two type of morphology, we designed and fabricated a stiffness controllable mechanism similar to the biological inter-layer jamming as in Fig. 3. We investigate two fastening mechanisms fabricated using active single wire or double wire SMA hooks and passive heat resistance loops, implemented on a heat resistance fabric. The hooks are trained to a circular shape using high electric current while they are fixed around circular wooden sticks with 2.2 [mm] diameter and loops are simply sewn on the second fabric layer. Placing the two fabric layers near each other and activating the hooks result in interlocking between the layers similar to natural Velcro mechanisms. A set of experiments are designed and carried out in the next sections to verify the characteristics and performance of this design.

III. EXPERIMENTS

We carried out a set of experiments to verify the performance and characteristics of our active velcro design. First, the current-temperature characteristics of the SMA wires are investigated experimentally. Next, a set of pulling tests are carried out for near stationary quasi-static and constant speed sliding movements of single active hooks with two different active attachment morphology, a single wire hook-hook system and a double wire hook-loop system. Finally, shear force response for three setups with different number and density of hook-loop pairs are measured in quasi-static and constant speed sliding movements.

A. Current-Temperature Characterization

We tested three different type of SMA wires with different diameters (RVFM SMA Wires with 0.006" and 0.004" diameters from www.rapidonline.com and Nitinol SMA wire with 0.01" diameter from www.kelloggsresearchlabs.com) to and each wire transition temperature is reported in table I. The transition temperature is crucial to predict the SMA wire response for different Pulse-width modulation (PWM) current signals. The experiments are conducted by using a K-Type fibre thermocouple, thermocouple amplifier

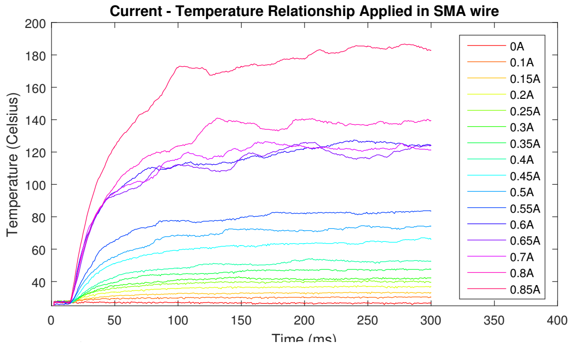


Fig. 4. The result of SMA wire temperature characterization for a SMA wire with diameter of 0.1 mm

MAX31855 breakout board by OLIMEX and an Arduino Mega2560 micro-controller with free air convection in the room temperature (27 °C) and for 3 seconds each. The results for the wire temperature against various current amplitudes from 0 to 0.8 [A] with a constant 24 [V] input voltage and sampling time of 10 [ms] is presented in Fig. 4. The 50 [mm] long sample of the SMA wire with 0.004 inch (0.10 mm) diameter and the resistance value of 150 [Ω/m] is found to have the fastest response to the electrical current input due to its high resistance value and small diameter. The optimal working temperature of SMA is found to be 80 °C, with electrical current of 0.6 [A], where the wire temperature become unstable for higher temperatures.

B. Single Active Hook Pulling

In order to analyze the performance of SMA hooks, a simple thermomechanical analysis is used where the thermic behavior of the SMA hook is compared to its mechanical properties, resisting pulling force in this case. Two different types of hook designs are tested where the resisting pulling forces for a hook-loop and hook-hook pair are measured for different amplitudes of activation current. The first model is a hook-hook system where hooks are built from a single wire and both hooks are needed to be activated and in contact to form a close electric circuit and activate. This morphology results in a weaker connection as the current flows from one hook to the other which leaves the tip of the hooks inactive. The second morphology is a hook-loop system which uses double wire hooks and passive loops as in Fig. 3 where the current flows only through the hooks. The tests are conducted using SMA wires with three different diameters 0.010” (0.25 [mm]), 0.006” (0.15 [mm]) and 0.004” (0.10 [mm]) and the following two parameters have been investigated:

- **Maximum Resisting Force:** The resistive force of the hook versus the displacement of the hook is measured for different amplitudes of input electric current. The maximum value recorded for the resisting force is used to identify the strength of the hooks in maintaining their position while resisting against exterior forces.
- **Maximum Distance of Extension:** This parameter reveals the concept of stiffness which strongly correlates to elasticity and plasticity of the body. Elasticity is the ability of a material to regain its original configuration after being deflected under a force, while it adapts to the force without being broken. On the contrary, plasticity can be described as the irreversible deformation capability of a material. In case of an alloy under pure extension, usually an elastic deformation follows by an irreversible plastic deformation after the yield point and then the fracture happens at the fracture point. Observing a hysteresis loop in the loading and unloading cycle of a system reveals its combined elasticity and plasticity characteristics. This test is carried out to reveal this property of the SMA hooks.

The results for three set of experiments are reported in this paper, a single wire hook-hook system with 0.010 inch (0.25 mm) SMA wire (Fig. 5a), a single wire hook-hook system with 0.006 inch (0.15 mm) SMA wire (Fig. 5b) and a double wire hook-loop system with 0.004 inch (0.10 mm) SMA wire (Fig. 5c), where hooks are trained with similar curvature diameters of (2.2 [mm]).

The result of the force measurement for 0.010 inch (0.25mm) SMA hooks is presented in Fig. 5a. The resisting pulling force vs. displacement, maximum elongation at the disengagement point vs. the input electric current and the maximum resisting force vs. the input electric current are plotted. The results demonstrate significant increase in the force magnitude when the applied electrical current increases. The maximum pulling force is 0.577 [N] for the electrical current of 1.5 [A] and maximum elongation of 0.113 [mm]. Increasing the current, reduces the maximum elongation distance before disengagement in this case. This is because of the increased stiffness of the material that limits the flexibility of the hooks and as a result, the hooks disengage with higher resisting force but less deflection and smaller overall elongation.

The second test is carried out on a single wire hook-hook system with 0.006” (0.15 mm) diameter SMA wire and the results are presented in Fig. 5b. The maximum force achieved is 0.12865 [N] which is slightly lower than the maximum force generated by the 0.010” diameter sample and the maximum elongation length is higher (2.2285 [mm]). The SMA wire with smaller diameter requires smaller electric current of 0.4 [A] to achieve its maximum pulling force. Having thin SMA wires with high resisting force is required for a wearable electro-active Velcro mechanism to achieve better flexibility and higher stiffness range with lower activation electric current. However, the flexibility and low activation current are more important as the small resisting force can be compensated by placing more number of electro-active hooks in parallel. The maximum elongation length of the system with smaller wire diameter is smaller because of the smaller achieved stiffness. This prevents the inactive length at the hooks’ tip to have enough time to fully activate after coming in contact and results in a weaker resisting force.

The third experiment utilizes double wire hooks in a hook-loop Velcro mechanism, as described in Fig. 5c, where a 0.004” diameter SMA wire is used. With a presumption that the maximum pulling force of this SMA wire in single wire topology will be less than that of the 0.006” diameter wire sample, doubling the number of physical contact and activation of the full length of the hook result in a higher maximum pulling force than expected. In contrary to the single wire hooks, for this morphology, the maximum deflection at the disengagement point for different input electric currents are almost equal and the maximum elongation even slightly increases for higher input currents. This is because of having a passive loop and two working wires in parallel for the double wire case with fully actuated hook length while in the hook-hook morphology the hooks’ tip remains inactive and both sides of the fastening mechanism deflect. The resisting force vs. elongation profile for different actuation current remains similar despite the change in the maximum force and elongation values. The resisting force changes almost linearly against the deflection length for the single wire hook-hook system, while this relation is linear for the first half of the full elongation stroke (3 [mm]) and becomes nonlinear afterwards in the case of the double wire hook-loop system. There is a sudden %40 drop in the recording force after 4.2 [mm] of elongation which indicates that one of the two parallel wires is disengaged and only one wire remains active and in contact with the loop. This is only possible if the hook wire twists while it bends for large deflections which indicates that the prediction of the behavior of this morphology is more complex compared to the single wire hook-hook system. The achieved maximum pulling force is 0.1261 [N] after an elongation of 4.23 [mm] in the double wire hook-loop sample which is slightly lower than the maximum force generated from the 0.006” diameter SMA wire hook-hook system. This shows better pulling force and flexibility and lower activation energy in case of double wire morphology with a smaller wire diameter.

Finally, the double wire topology with smaller diameter of 0.004” in an active hook and passive loop system is found to be have better characteristics than the single wire topology with bigger diameters and active hooks on both sides. This morphology shows to be easier to fabricate and have better performance characteristics, durability and robustness with the following considerations; with dual active sides in the case of the hook-hook system, there is a bigger risk of losing contact after fabrication and during the activation of the system on a deformable fabric; the single wire hook-hook system is more complected to fabricate as the both sides need to be connected and powered by the electric current; the double wire hook-loop system offers possible utilization of the existing Velcro fabrics with loops in the market; and the double wire morphology is observed to increase the pulling force while maintaining the same elongation range for different input electrical currents. the double wire morphology with 0.004” diameter SMA wires in a hook-loop system is employed for the fabrication of the active hook arrays and later in the stiffness controllable fabric layer.

C. Active Hook Arrays

Despite the promising %300 increase in the resisting force by activating the SMA hooks, the resulting force from a single pair of hook and loop is not high enough in magnitude to be used in fabrication of stiffness controllable layers. To achieve a reasonable force a number of active hooks should engage in parallel on the attachment layer. It has been observed that the loops need to be bigger and placed randomly to achieve stronger engagements with the hooks and the random number and quality of engagements is probabilistic [11]. We investigate this by comparing the resisting force of one hook against three parallel hooks that placed and trained carefully to engage with the loops at the same time (Fig. 6). the results show the maximum resisting force from three parallel hooks is slightly bigger than twice the force from one hook. However, the maximum force for the three hook sample occurs after %50 more elongation compared to place the maximum force is observed for the single hook sample. It shows that the parallel hooks does not fully engage at the same time and elongation distance, hence the pulling force is not as high as expected from a perfect

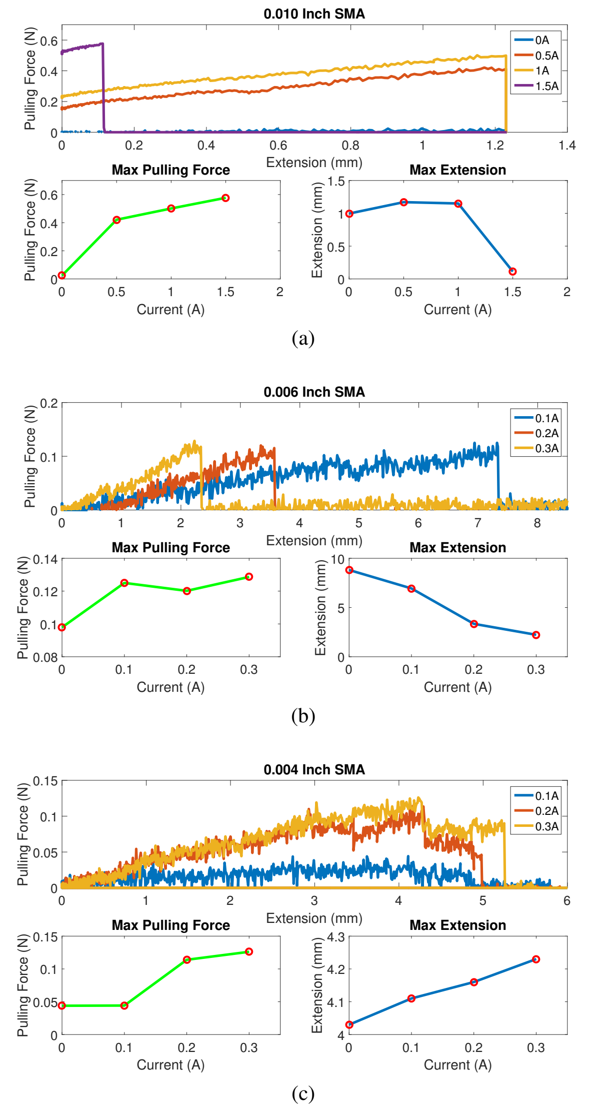


Fig. 5. Force-Extension profile for different input currents, 0.010” (a), 0.006” (b) and 0.004” (c) diameter SMA wires.

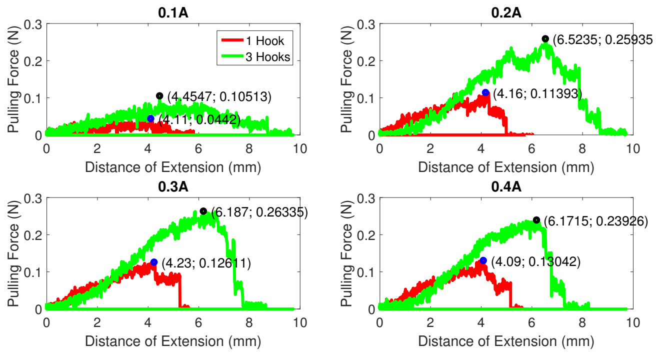


Fig. 6. The effect of increasing the number of hooks from 1 to 3 on the resisting force

parallel engagement and the elongation distance where the maximum force is observed is more than the case of a single hook. This means that at a given time, not all of the hooks but some with a probability come in contact and fully engage with the loops.

To investigate the effect of the hook numbers and densities for our active attachment design, first, nine active hooks in a 3x3 arrangements with three different densities are fabricated by soldering the hooks on a prototyping breadboard; low density sample with 15 [mm] space between the hooks, medium density sample with 10 [mm] space and high density sample with 5 [mm] space. The loops are half circles with 10-20 [mm] diameter.

The plot for the resisting force vs. the load cycle time for a 200 [mA] input current shows a %23 higher maximum force for the high density sample vs. the medium density one and %34 higher maximum force for the medium density sample vs. the low density one (Fig. 7). Increasing the input current from 200 to 300 [mA] causes more increase in the maximum force of the medium density sample (%5) compared to the other versions (%4 for the high and %0.2 for the low density sample) and results in %1 reduce in the difference between the maximum force of the high and medium density samples while a %4 increase in the maximum force difference between the low and medium density ones. increasing the current further results in %7 increase in the maximum force of the medium density sample but no significant changes in the maximum force of the other two samples. Two peak forces are observed, a small one at 10 [s] and a bigger one at 15 [s] time. Position of the peak forces are similar for all the samples because of similar geometry of the hooks and the loop; however, increasing the input current reduces the difference between the forces at the peak points, resulting in a smoother profile with a sharp rise at the beginning and a sudden fall after the second peak point (where all the hooks are disengaged). This shows that the input current has an effect on the distribution of the engagement probability over time and displacement. This is more obvious for the high density sample. We continue with the medium density sample because of similar peak force value to the high density one and easier fabrication.

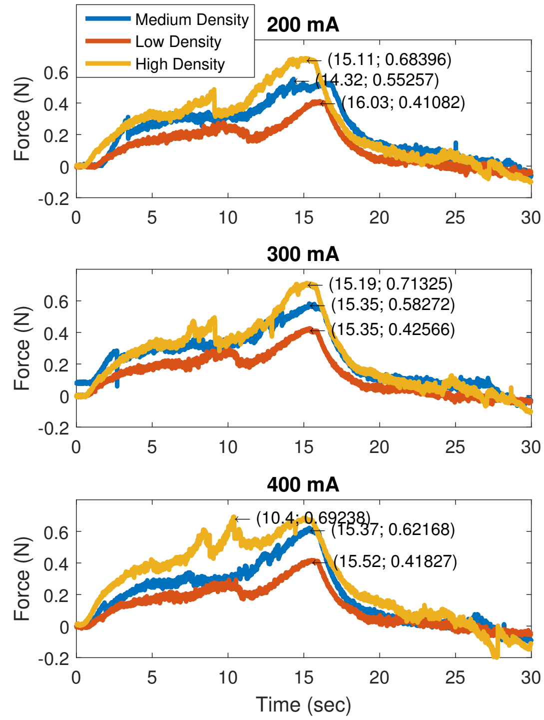


Fig. 7. The effect of different hook densities and arrangements on the resisting force of the active hooks. Low density: 3x2 array with 15 [mm] spacing, medium density: 3x3 array with 10 [mm] spacing, high density: 3x5 array with 15 [mm] spacing.

Then we tested the resisting force of three samples with different number of hooks, six hooks in a 2x3 arrangement, 9 hooks in a 3x3 arrangement and 15 hooks in a 3x5 arrangement as in Fig. 8. The observed characteristics are similar to the results from the tests on the different density samples. The maximum force is not proportional to the number of the hooks, but increases as the number of the hooks increases (%40 increase from 6 to 9 hooks and only %3 increase from 9 to 15 hooks). Similar to the medium density case, higher variability in the maximum force vs. the input current is observed for the sample with 9 hooks sample (%225 increase from 0.3 [A] to 0.5 [A] in the input current) compared to the 6 hooks (%23 increase) and 15 hooks (%41 increase) versions; however, a smoother profile is observed for the sample with 15 hooks. An optimum number of hooks can be found to achieve the maximum value and variability of the force which is suitable for the applications with static force requirement; however, smoother force profile is needed when dynamic movement is necessary.

IV. Future Work

As the result of this research, the electro-active velcro mechanisms with double wire hook design and 10 [mm] spacing is implemented in a 3x7 arrangement (21 hooks in total) on a 0.45 [mm] thick deformable heat resistance fabric to be used as a wearable stiffness controllable layer for wrist rehabilitation purpose (Fig. 1). We plan to investigate

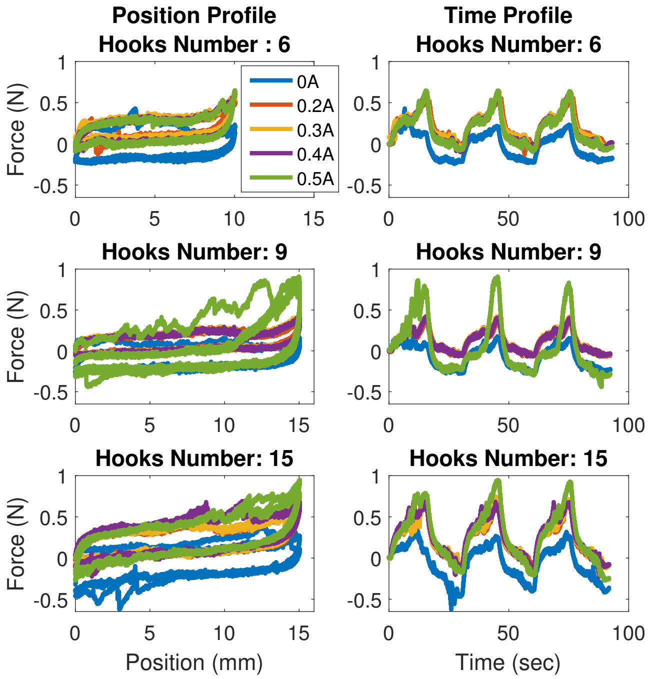


Fig. 8. The profiles generated from three samples with similar density (10 [mm] spacing) and different number of hooks during dynamic pulling tests.

the performance of our wearable active velcro layer in controlling the stiffness of robotic and human joints and its possible application as a wearable stiffness controllable fabric for general purposes. To this end, we are going to investigate a control framework to achieve static and dynamic stiffness variability using our novel wearable active-velcro mechanism. This requires mathematical models for the single active SMA hook-loop system and a probabilistic model to predict the peeling and shear force of the attachment mechanism which will be addressed in the future.

V. CONCLUSIONS

This research presents a working prototype of a stiffness controllable fastening mechanism based on an electro-active SMA Velcro design inspired by natural micro active hooks found in plants and animals. Contradicting to the conventional passive Velcro mechanisms, it has the capability of adopting to external forces to maintain the structure of its supported layer by active modulation of the Velcro attachment system stiffness. The SMA wires are used to fabricate the active hooks which are actuated via thermo-electric manipulation using Lenz-Joule heating method. We showed the experimental results for the effect of varying the temperature of SMA Velcro, their density and number on the resisting force profile in quasi-static and dynamic pulling and sliding movements, to provide new insights about the novel design approach of using active hooks for stiffness modulation of thin layers. Our findings support future application of active Velcros for implementation of wearable and deformable stiffness controllable fabrics.

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