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Analysis of driving forces of 3D knitted shape memory textile actuators using scale-up finite element method

SangUn Kim[1,2] and Jooyong Kim[1,2*]

*Correspondence:
jykim@ssu.ac.kr

[1] Smart Wearables Engineering, Soongsil University, Sangdo-dong, Dongjak-gu, Seoul 156-743, Korea
[2] Organic Materials and Fibers Engineering, Soongsil University, Sangdo-dong, Dongjak-gu, Seoul 156-743, Korea

Abstract

The shape memory textile actuator uses a shape memory alloy that changes its crystal structure according to temperature and then returns to its initial shape, which is suitable for wearable applications that value wearing and portability. The shape memory effect of returning to the initial shape and the complex fabric structure influence each other, and accordingly, various drives have been measured in many studies. Therefore, in this study, the driving force, which is the most important physical property of the shape memory textile actuator, was analyzed through a scale-up finite element analysis. In the wire scale, a shape memory alloy wire was obtained for an analysis of the mechanical and thermal properties through tensile tests and DSC, and in the unit cell scale, a 3D knit structure was modeled using the Texgen and Weftknit programs. Finally, a supercell of size 5 × 5 was subjected to external deformation by displacement and heating conditions using disposition through the ANSYS program. The driving force was measured through microanalysis. Subsequently, the driving force of the manufactured shape memory textile actuator was compared and analyzed to determine the suitability of this method. Furthermore, the direction of subsequent studies was mapped based on the analysis presented on the differences in the maximum driving force and error rate.

Keywords: Shape memory alloy, Shape memory textile actuator, Finite element analysis, 3D knit structure, Textile actuator

Introduction

Extensive research has been conducted on developing shape memory alloys as actuators through shape memory effects, and their applicability is being verified in various fields. The shape memory alloy actuator has a working density that is 100 times that of a commercial electric motor and can lift 25 times its weight (Jani et al., 2014). In the smart wearable field, the development of a shape memory textile actuator made of a shape memory alloy that values the comfort and convenience of the wearer is being actively pursued. Various studies have been conducted on devices, such as smart curtains that automatically open in the morning sunlight using a stitching method, smart shirts that return to the shape of an initial shirt at a certain temperature or higher, and smart fire suits that knit the shape memory alloy to protect the skin at high temperatures (Chan Vili, 2007; Kim et al., 2009; Lah et al., 2019; Park & Park, 2019; Stylios & Wan, 2007). In this study, we determine the mechanical scale and variability of the actuating model of the shape memory textile actuator for easy application in many fields.

Finite element analysis of complex shape memory textile actuators requires the measurement of the mechanical properties of wire-scale shape memory alloys before fabrication. With the development of computer and computer material dynamics, many researchers have suggested finite element analysis modeling and methods for shape memory alloys. (Auricchio, 1995; Auricchio et al., 1997; Brocca et al., 2002; Divringi & Ozcan, 2009; Rebelo et al., 2011) Because the operating temperature and mechanical properties of the shape memory alloys vary depending on the manufacturer, it is necessary to measure the mechanical properties of the shape memory alloy (Kennedy, 2013). In a previous study (Alazzawi & Filip, 2019), the deformation and stress caused by the shape memory effect were measured after adding weight to a C-shaped shape memory alloy in relation to three types of mechanical properties. Using finite element analysis of wire-scale shape memory alloys, this study confirmed the deformation by adding the mechanical properties of shape memory alloys through differential scattering calorimetry (DSC) measurements and tensile tests. With respect to the measurement sample, the physical properties of the shape memory alloy manufactured by SMA Co., Ltd., Korea were confirmed.

After analyzing the physical properties of the shape memory alloy in the wire scale, a finite element analysis of the shape memory alloy in the unit cell scale, is crucial for a complete analysis (Lomov et al., 2011; Skalitzky et al., 2018; Verpoest & Lomov, 2005). In this study, Texgen, an open-source software developed by Nottingham University, was used to model and analyze the structure of the fabric, based on a finite element analysis of the answer program by modeling the 3D unit cell of the fabric (Lin et al., 2011). The driving force of the shape memory textile actuator becomes stronger as the amount of shape memory alloy per volume increases, which is influenced by the diameter of the shape memory alloy and the textile structure (Kim et al., 2009; Lah et al., 2019). Finally, we examined the difference between the displacements caused by the tensile test and recovered during the operation with an actual universal testing machine for each model and analyzed the proportion of each model.

An actual knit textile structure was manufactured for comparative analysis with respect to the results of the model obtained through finite element analysis of the unit cell scale. Because of the thick diameters of 0.3 and 0.5 mm, both structures were manufactured manually, and the shape memory training process was performed to take into consideration the complex initial shapes. Finally, the finite element analysis and operation of the actual shape memory textile actuator were compared and analyzed.

Finally, this study is a study to predict whether the driving force of shape memory textile actuator before making with cost and time through finite element analysis with mechanical and thermal properties in wire scale and 3D model in the unit cell and they are suitable for many applications.

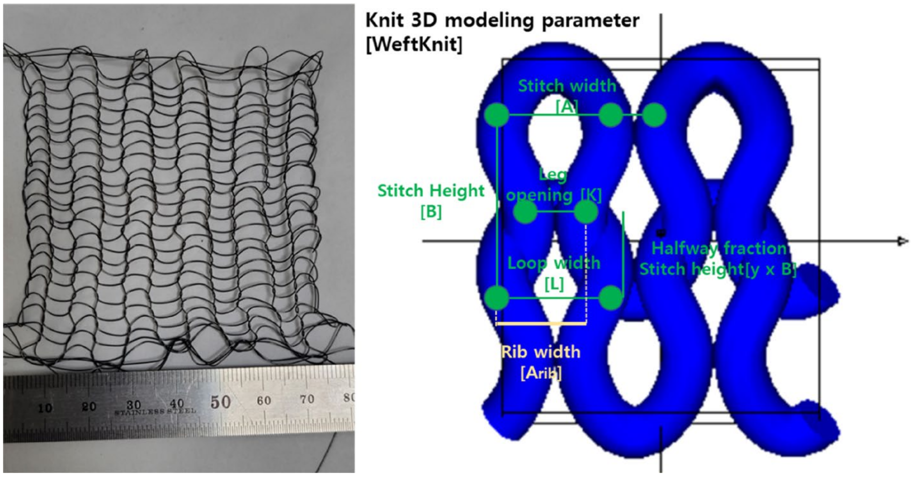

Fig. 1 Parameters of the knit unit cell structure and shape memory textile actuator

Table 1 Knit parameters of shape memory textile actuator 0.3 mm, 0.5 mm

Shape memory alloy diameter (mm)	Knit parameter					
	Loop width [L] (mm)	Leg opening [k] (mm)	Stitch width [a] (mm)	Rib width [A_{rib}] (mm)	Halfway fraction stitch height [y_b] (mm)	Stitch height [B] (mm)
0.3	9	6	15	7	5	7
0.5	10	8	15	8	5	6

Methods

Mechanical/thermal properties of shape memory alloy (wire scale)

Shape memory alloy wires of diameters 0.3 and 0.5 mm were manufactured using nickel and titanium in 1:1 ratio manufactured by SMA Co., Ltd., Korea. The mechanical and thermal properties were evaluated using DSC analysis and tensile testing. In the DSC results, the starting and finishing temperatures of the martensite state and the starting and finishing temperatures of the austenite state were determined from the DSC results graph, and the actual operating temperature that is the austenite state finish temperature was obtained. In the stress–strain curve of the tensile test, the Young's modulus at room temperature and the operating temperature were calculated.

3D modeling of shape memory textile actuator (unit cell/supercell scale)

To model the finite element analysis, the Texgen and Weftknit programs were used, and the shape memory textile actuator structure to be analyzed was modeled. As shown in Fig. 1, 3D modeling was implemented by adding each knit parameter of each shape memory textile actuator unit cell and it is organized in Table 1. Finite element analysis was performed using the ANSYS program with supercell that repeated 5×5 unit cell model.

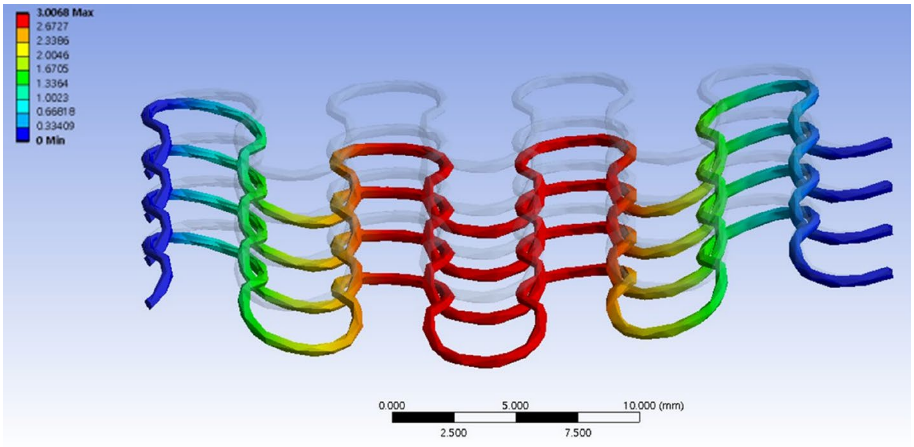

Fig.2 Finite elements analysis of shape memory textile actuator using ANSYS

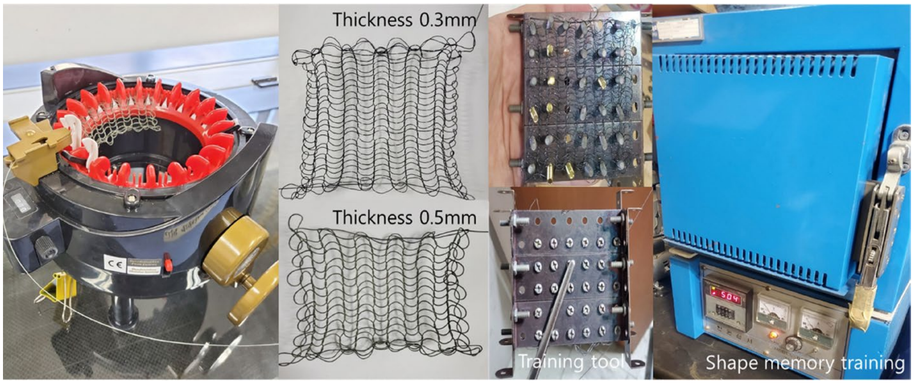

Fig. 3 Production and training process of shape memory textile actuators

Finite element analysis of shape memory textile actuator (supercell scale)

We created a mesh structure of the shape memory textile actuator supercell modeled as an ANSYS static structure and to check the force during the operation; the loading was applied to the z-axis at 0.22, 0.32, and 0.42 mm, considering the thickness of each shape memory textile actuator as shown in Fig. 2. The driving force during the operation was obtained by multiplying the loading area applied to a sample of average stress by the normal stress in the z-axis when heated from 22 to 40 °C.

Comparison with real shape memory textile actuator

As shown in Fig. 3, a shape memory textile actuator in the form of a knit with diameters 0.3 and 0.5 mm was manufactured using an actual small knitting machine, and the shape memory training was performed at 500 °C for 15 min. The operating force was measured under the same conditions as the finite element analysis by Joule heating at 1 A series resistance above the operating temperature as shown in Fig. 4. This was compared with the results of the finite element analysis.

Fig. 4 Measuring driving force of real shape memory textile actuator with Universal Testing Machine

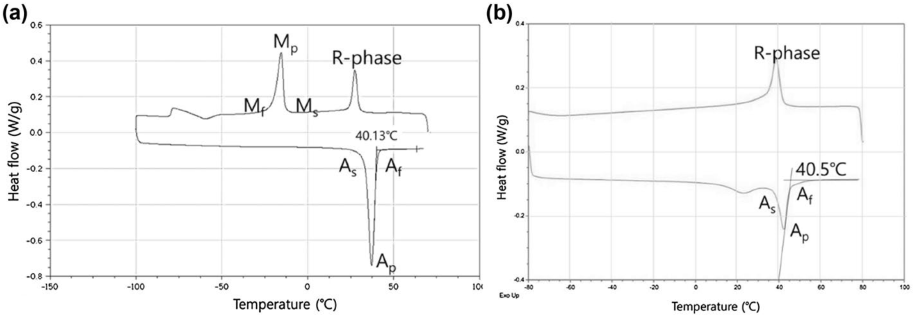

Fig. 5 DSC results of the shape memory alloy wire of diameter 0.3 mm (**a**) and 0.5 mm (**b**)

Results

Mechanical and thermal properties shape memory alloy in wire scale

The shape memory alloy DSC results for 0.3 mm and 0.5 mm in wire scale are shown in Fig. 5, and the operating temperatures of the shape memory effect were 40.5 °C and 40.13 °C, which were obtained based on the austenite finish temperature. The results of the tensile test of the shape memory alloy wires were measured below the operating temperature and above the operating temperature, as shown in Fig. 6. The Young's modulus was calculated using the range of Hook's law in the stress–strain curve and illustrated in Table 2.

Comparison between the real shape memory textile actuator and finite elements analysis

The number of nodes and elements of the finite element analysis model of the shape memory textile actuator with respect to the modeling using ANSYS was 52,759 and 27,153, respectively, at 0.3 mm. At 0.5 mm, 58.221 nodes and 28.618 elements were

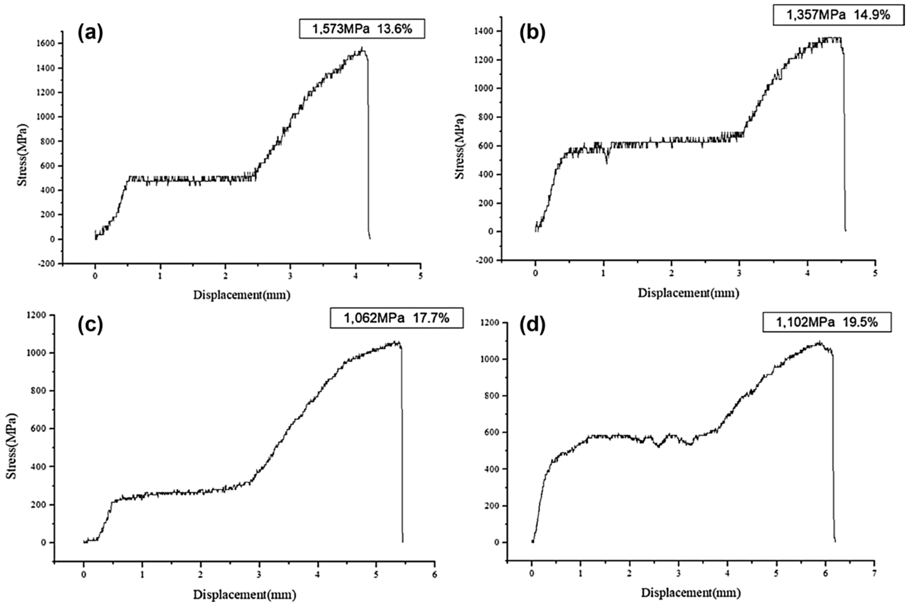

Fig. 6 Tensile test results of the shape memory alloy wire: 0.3 mm, 22 ℃ (**a**); 0.3 mm, 45 ℃ (**b**); 0.5 mm, 22 ℃ (**c**); and 0.5 mm, 45 ℃ (**d**)

Table 2 Wire scale mechanical properties of shape memory alloy wires 0.3 mm, 22 ℃ (a), 0.3 mm, 45 ℃ (b), 0.5 mm, 22 ℃ (c) and 0.5 mm, 45 ℃ (d)

Shape memory alloy	Wire scale mechanical properties		
	Strain	Stress (MPa)	Young's modulus (MPa)
(a)	0.0167	500	30,012
(b)	0.0167	600	36,014
(c)	0.0161	200	12,422
(d)	0.0161	500	31,055

composed. The data comparing the measured force with the actual force. In Fig. 7a, the error rates of the maximum operating force are 0.24%, 3.48%, and 5.18% for the actual data of 0.22, 0.32, and 0.42 mm, respectively, of the shape memory textile actuator of diameter 0.3 mm. In Fig. 7b, the error rates of the 0.5 mm shape memory textile actuator are 16.06%, − 15.98%, and 6.73%.

Discussion

Many studies have suggested the application of the shape memory alloy as a textile actuator because of its good mechanical work density. However, since there are many types of shape memory alloys with different properties, unexpected properties were often obtained even with the same weaving method. So this study referred to finite element analysis with wire scale to the actuator and confirmed the applicability of this analysis by comparing real textile actuators.

As a result of the mechanical properties of the wire scale, it was seen that Young's modulus value increased above the operating temperature. The stress value increased

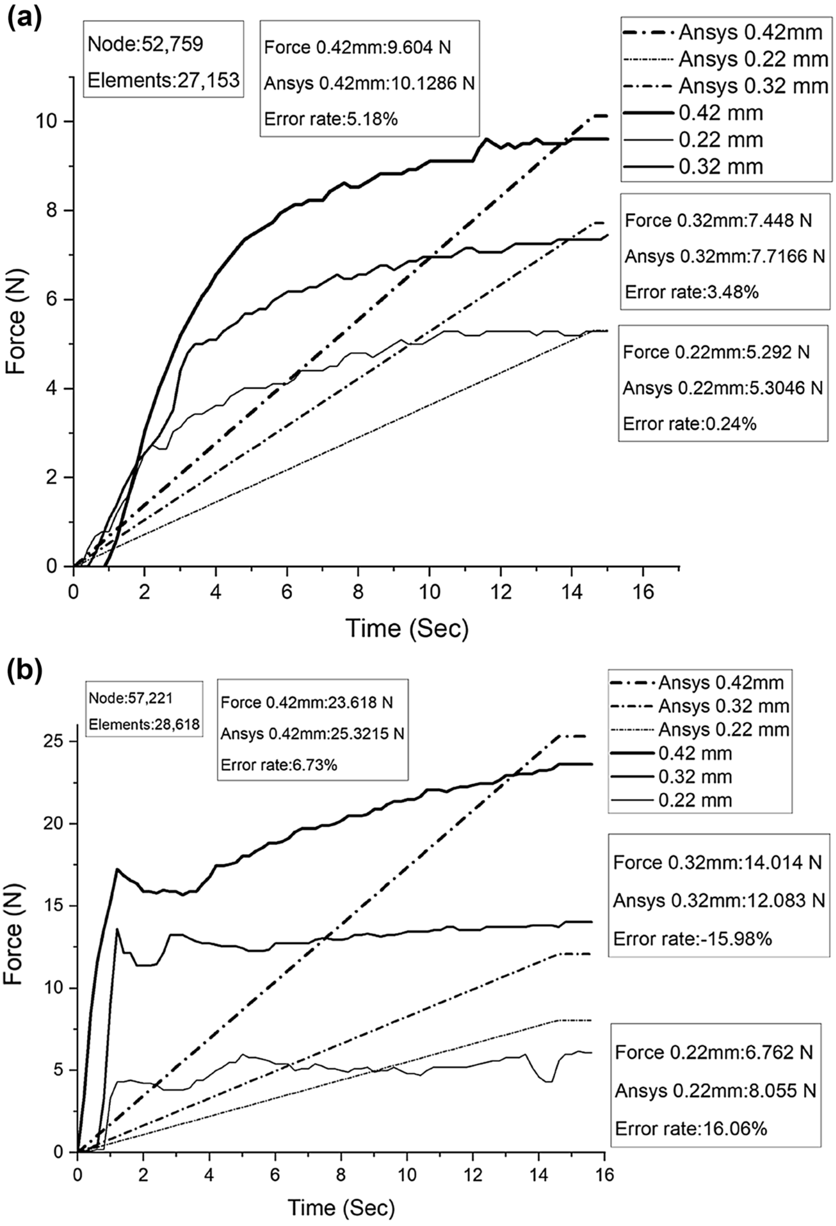

Fig. 7 Comparison of the actuator driving force between the finite elements analysis model and experimental data of the shape memory textile actuator for diameters: 0.3 mm (**a**) and 0.5 mm (**b**)

under the same strain, and the increase rate of the shape memory alloy with a large diameter was higher. Accordingly, it was found that the young's modulus increased significantly and the driving force returning to the initial shape was larger.

In addition, in the DSC result, which shows the thermal properties through heat flux, it was possible to confirm the temperature sections of the martensite and austenite states, which are the two crystal structure states of the shape memory alloy, and Since the start of returning to the initial shape memorized at high temperature starts at the temperature at which the austenite crystal structure finished, it was found that it can be driven at about 40 °C or more from DSC.

Upon comparing the results of the finite element analysis of the shape memory textile actuator through ANSYS and the driving force of the actual actuator, it was observed that smaller the diameter, the lower is the error rate with the actual operation. This is because the unit cell of the textile actuator manufactured by knitting a shape memory alloy wire with a small diameter is more uniform in repetition. During the operation, the overall movement deviated significantly from the analysis result.

It was observed that the driving force of the same shape memory textile actuator increased with loading, but the difference with the finite element analysis with respect to the actual stiffness and driving force increased. It was observed that the driving force of the textile actuator reduced above a certain loading.

Conclusions

Several studies have been conducted on actuators using shape memory alloys. In particular, there have been many studies on their application as textile actuators in fields where wearability and portability are favored, because they are lighter and less bulky than conventional electric motors. A research limitation is that the actuator performance differs depending on the thermal characteristics, fabrication method, and measurement method. This study is to suggest the analysis driving force of shape memory textile actuators with different characteristics wires and 3D textile models before making real actuators for saving cost and time making actuators with complicated processing. In the future, by adding the other characteristics or analysis more scales can improve suitability of shape memory textile actuators for many applications with different wires and models.

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Author contributions
SUK originated the research idea, collected data and drafted the manuscript under the guidance of JYK, their supervisor. Both authors read and approved the final manuscript.

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Availability of data and materials
The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

Author's information
SangUn Kim, Ph.D. student, Soongsil University, Seoul 156-743, Korea. Jooyong Kim. Ph.D., Professor, Soongsil University. Seoul 156-743, Korea.

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