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A smart orthopedic compression device based on a polymeric stress memory actuator

Bipin Kumar [a], Jinlian Hu [b,*], Ning Pan [a,*], Harishkumar Narayana [b]

[a] Division of Textiles, Biological & Agricultural Engineering, UC Davis, CA 95616, USA
[b] Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Kowloon, Hong Kong

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ABSTRACT

In current practice of compression therapy, there has been a challenge of compression controlling and need for multiple devices to achieve different functions. Herein, the potential of a thermal-sensitive memory polymer, namely, polyurethane (MPU), is explored in designing a prototype that acts as a flexible bandage system to provide dual benefits (heat and pressure) simultaneously for a desired compression. After preconditioning, the thermomechanical behavior of the MPU becomes repeatable and consistent, which can be programmed to remember (store) and retrieve reversibly a prescribed internal stress, responsive to an external stimulus around its transition temperature (T_{trans}). The smart bandage system is then built using the MPU actuator which integrates electric resistive wires as both a heat source for thermal therapy and stimulus for trigger control. The compression can also be easily switched between *static* and *dynamic* (massage) modes using a pro-set thermal stimulus. This paper also addresses several challenging issues and design considerations for the prototype. Theoretical analyses have been applied to predict the device performance, showing excellent agreement with experimental results. This work sheds insights for broadening the applications of *stress memory* and for engineering smart products needing stimulus responsive forces such as dynamic cushions, pressure garment and electronic actuators.

1. Introduction

Shape-memory polymers (SMPs) have stimulated research interest from both academia and industries over the last decades, because of their ability, after the so-called programming process, to memorize any shape change experienced so as to revert back to their original shape once needed in response to an external stimulus such as heat [1,2]. Owing to this unique property, SMPs have found increasing applications in aerospace, biomedical, transport, construction, electronic, textile and consumer products where the potential of shape fixity or recovery is exploited for desired functions [3–6]. Recently however, several other associated memory phenomena including *stress memory* [7], *temperature memory* [8], *chrome memory* [9] and *electric memory* [10] have also been reported in such polymers, thus it seems more appropriate therefore to call them memory polymers (MPs) in general.

Stress memory refers to a phenomenon where the internal stress in a MP can be programmed, stored, and retrieved reversibly with an external stimulus [7]. This opens several new research domains for MPs where stimuli-responsive forces are required/involved, including in sensors, sportswear, compression garments, massage devices, nerve conduits, bone tissue engineering, artificial muscles and dynamic mattress. Herein, an attempt has been made to tap the potential of *stress memory* in a thermal-sensitive MPU actuator to demonstrate the benefits of controlled stress (compression) in conjunction with thermal therapy for problems concerning orthopaedics.

Compression is the main core in many orthopedic treatments related to muscle pain, chronic venous disorders, lymphedema, and many other lymphatic diseases [11]. Applying external compression to an affected body site reduces the fluid loss from the vessels, thereby prevents swelling so as to promote fast healing of soft tissue injuries. The compression applied can be static or dynamic in nature. In *static* mode, constant compression is maintained over long period of time, especially in venous ulcers, to assist venous return (deoxygenated blood moving back up to the heart) [12], whereas the *dynamic* mode is recommended to provide alternating massage to the affected parts [13,14] In addition to compression, simultaneous heat treatment offers additional benefits in bringing blood to the affected area by opening up blood vessels [15], thus increasing blood flow with nutrients and oxygen so as to reduce pain in joints and relax sore muscles, ligaments, and tendons [16,17]. As a result, hot compress devices have been produced and recommended for muscle aches, cramps, stiffness and arthritis to relive tired eyes, neck pain, shoulder pain, back muscle pain, pain at joints, etc. [18–20].

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* Corresponding authors.
E-mail addresses: bipiniitd18@gmail.com (B. Kumar), tchujl@polyu.edu.hk (J. Hu), npan@ucdavis.edu (N. Pan).

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In conventional systems of using bandage or stocking for compression in chronic venous disorders, there has always been the problem of pressure control [21,22]: it is difficult to achieve a targeted level of pressure as the pressure level depends on many complex, dynamic and intertwined parameters including the device materials, applied pre-extension, wrapping procedure, size and shape of bandaged parts, etc. Further when a *dynamic* compression (massage therapy) is required, additional unit such as the intermittent pneumatic compression (IPC) has to be attached to the device [13], which is usually noisy, bulky, and once attached requires immobility from the patients [23]. Additionally, if a heating therapy is needed in conjunction with compression for muscle aches or cramps, hot sleeves or towels is employed. Although some newer electronic devices have become available, where separate mechanical or electrical mechanisms are used to provide the functions, heating via electric wires, and compression by pneumatic bags or rotatory motors; they further complicate the system. To sum up, there are some critical limitations existing in the current approaches in heat and/or compression treatment, including most significantly the problem of pressure control, also separate source for heat and compression, design complexities and hence cost concern, etc.

This paper focuses on design and development of a bandage prototype that allows controlled/sustained compression and thermal functions both from a stress memory MPU actuator which, in response to a heat stimulus, triggers its function in modulating the level of internal stress. That is, if properly designed, this new device can deliver dual functions of heating and pressing simultaneously in one simple package, provided that the actuating temperature range of the MPU is properly selected to accommodate both functions. This paper addresses several important issues and design considerations for such prototype. Theoretical analyses have been conducted to understand the *stress memory* phenomena and predict the pressure levels generated. Experimental validations are also provided.

2. Materials and methods

2.1. Synthesis of the MPU

The MPU film was produced using segmented polyurethane via a two-step polymerization method [7]. Poly(ε-caprolactone) diols (PCL; Daicel Chemical Industries Ltd., Japan) of molecular weight of 4000 $\text{g}\cdot\text{mol}^{-1}$ was used as the soft segments, 4,4′-diphenylmethane diisocyanate (MDI; Aldrich Chemical Company, USA) as the hard segments, and 1,4-butanediol (BDO; Acros Organics) as the chain extender. First, MDI and PCL were mixed for 2 h at 80 °C to form the precursor. BDO was then added for crosslinking through a reaction lasted for another 1 h, while N,N′-dimethylformamide (DMF; Aldrich Chemical Company, USA) was used as the diluent to control the viscosity during the reaction to ensure proper mixing. A nitrogen environment was maintained for all the reactions, and the reaction temperature was controlled to be lower than 90 °C. Afterwards, the resulted polymer was poured into a pre-heated (100 °C) polytetrafluoroethylene mold and a MPU film sheet (~0.4 mm thick) was obtained. The weighted ratio of hard segment (MDI + BDO) to soft segment (PCL) was determined as 28/72. Multiple characterization techniques including DSC, TMA, SAXA, DMA, etc., were used to analyze the morphological and thermomechanical properties of the MPU film. More detailed descriptions can be found in previously published work [7].

To offer the heating and compression benefits simultaneously however, the selection of MP is very critical—a MP with too high a T_{trans} is not desirable for human body to bear. Therefore, it was necessary to prepare a MP with lower T_{trans} such that both heating therapy and compression activation could be achieved in a single batch. Several factors, such as molecular weight, ratio of hard/soft segment, crosslinking level, etc., can be controlled to tune T_{trans} for a MPU [2]. In this work, the melting transition of the soft segment crystals was found in the range of 25–55 °C, and the endothermic peak, i.e., T_{trans}, was at 42.63 °C.

Before assembling the MPU film actuator into the device, the MPU has to be conditioned and programmed (described below in Section 3) to achieve the functions desired, and the pressure generated can also be adjusted by programming the MPU actuator to different strain levels.

2.2. Development of the bandage prototype

A simple bandage prototype was then developed with three basic elements: (a) base fabric; (b) MPU film actuator; and (c) heating unit, as detailed in Fig. 1. The layers of base fabric are a normal woven fabric made from polyester yarns. The MPU film prepared above is used as the actuator for compression. For the heating element, a normal electrical heating wire made of copper (diameter = 1.8 mm; resistivity = $1.68 \times 10^{-8}\ \Omega\cdot\text{cm}$) was used. The wire is first twisted and secured using plastic tape fasteners, and then embedded between the fabric layers. The path of the embedded wire was shaped as square wave in order to obtain uniform temperature distribution (Fig. 1b). This design does not significantly affect the mechanical property of the device and allows sufficient flexibility for easy wrapping of the prototype over a curved surface. Carbon nanotubes or other fillers can also be used to generate heat, but these particles can compromise the mechanical properties of the MPU. The fabric layers were then stitched together along the seams to secure the location of the heating layer for safety and tactile comfort.

The MPU film actuator was then integrated with the base fabric using a Velcro *hook* and *loop* system attached to the film and fabric respectively. The Velcro strip (*hook*) is stitched to the end of the film along its width, and several Velcro strips (*loop*) to the fabric at different locations as shown in the Fig. 1c, thus allowing different sizes or different magnitudes of pressure. If just the thermal therapy is needed, one can detach the MPU actuator. In its fully developed form, the prototype can be easily wrapped onto the body part and held in position by the Velcro fasteners.

2.3. Experimental methods

For all the thermomechanical tests conducted in this study, the testing machine was composed of a tensile tester (Instron 5566), for loading and unloading, anchored with temperature chamber for heating and cooling. The film specimen gauge length was 50 mm and 10 mm in width. The heating was provided at a constant heating rate (5 °C/min), while the cooling was done at the ambient temperature (~20 °C).

For the power supply to the heating wire, a single output DC power source (MCH model K3050) was used with variable voltage levels up to 30 V. To test the performance, the assembled prototype was wrapped on a solid tube (circumference: 23.5 cm) mimicking the body part that also provides an external constraint (strain) to the MPU actuator. The temperature change on the surface of the device at different voltage levels is measured using a digital infrared thermometer (Fluke 62 MAX; Model no: 130474), and the pressure measurement was done using a Kikuhime™ pressure sensor. The experimental set-up is shown in Fig. 2.

3. Theoretical and design considerations for the MP actuator

If a compression bandage is mounted over a curved body section (limb or neck), the applied interface pressure is related to the properties of bandage and body part known as the Laplace Law: [24–26].

$$P = \frac{\sigma \times h}{r} \tag{1}$$

where P is the interfacial pressure (N/m^2), σ is the internal stress (N/m^2) in the bandage and h is its thickness, and r the radius of the limb. Once the bandage is stretched to fit to a limb, a constraint (strain) and hence a stress σ is established in the bandage. It is therefore possible