Design and Development of a Garment-based, Dynamic Compression System using Active Materials*

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Abstract—**Compression is ubiquitous and is used in many applications including clinical interventions, yet remains largely understudied as a haptic modality. This work involves the development of garment-based compression technologies that are dynamic, low-mass, and remotely controllable. Shape memory alloys (SMAs) (a form of active material), embedded into garments are capable of creating spatially- and temporally-dynamic compression on the body in an unobtrusive form factor. The developed technologies will serve as a platform to better understand the objective/subjective effects of compression on users. This work also enables new modes of interaction between users separated by distance, including the potential as novel tele-rehabilitation technologies to enrich the lives of those in need.**

INTRODUCTION

Compression is a ubiquitously-experienced sensation and is important for various healthcare applications to facilitate circulation (e.g., compression stockings) or to enhance psychological well-being through aiding relaxation (e.g., deep touch pressure [1] or massage therapy). Some characteristics of compression as haptic feedback include being similar to common human behaviors, able to invoke a range of attention capture depending on its compression input features, and is less attention-demanding (suitable for ambient feedback) [2]. However, in order to truly maximize the use of compression as a haptic modality, the objective/subjective effects of compression on the human body must be better understood. Compression can be modulated with varying input parameters including compression location, intensity, rate, and duration, providing an array of experiences. However, these factors have not been rigorously studied, and it is not yet known the optimal parameter set necessary to facilitate a desired haptic experience. Further, there is a lack of focus on using a garment form factor to distribute compressive forces onto larger areas of the body (i.e., the torso). The garment platform is ideal for creating compression due to its proximity to the body, direct access to large surface areas, and the social ubiquity of clothing – garment-based actuation provides a physically intimate yet low-profile solution. Conventionally, on-body compression with wearables are either (a) passive designs (e.g. elastic clothing, weighted vests), or (b) dynamic inflatable constructions (e.g., pneumatic inflatable garments). The limitation of these devices are in donning/doffing ease, mobility, and bulk [3]. Therefore, a key solution is to create an innovative garment platform that exceeds traditional actuation schemes (e.g. servos, pneumatics) by using embedded active materials that feature the ability to repeatedly and invisibly change shape when actuated. Here, shape memory alloy (SMA) coil actuators are used, given their prior success in producing controllable, repeatable compression (up to 225 mmHg) that scales with applied current [3]. This paper outlines the design and development of a garment-based, dynamic compression system with embedded SMA actuators, and outlines a plan to address the aforementioned research gaps when using computer-mediated compression systems.

I. SYSTEM DESIGN

A. Garment Design

Prior work has shown feasibility of SMA coil actuators in a compression garment system, tested on a small-scale (n=8) male user sample [4]. The study served as an initial pilot to investigate the subjective effects of on-body compression, but suffered from some limitations: the garment provided only a single compression intensity, was tethered to a benchtop power supply, used non-compliant Teflon^{TM} materials, and supported only a single user size and gender. This system has undergone significant system redesign to address these initial limitations, and the advanced prototype is presented herein. This upgraded dynamic compression system consists of an inner comfort layer, middle actuation layer, and outer covering (Fig.1). The inner comfort and middle actuation layer are connected through a front zipper (ease of donning/doffing). The inner comfort layer consists of a woven canvas fabric on the front, 3D spacer foam mesh with ventilation channels on the back (for heat management and back support), and heat

Figure 1. Garment-based dynamic compression system components and design. (A) Inner comfort layer and middle actuation layers; (B) Final men's and women's garment design with arm bands; (C) Women's garment worn on the body showing all system components

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insulation side panels (protecting user from heat generated by SMA actuation) positioned directly below the actuators. The middle actuation layer consists of a non-stretch cotton/aramid blend, with SMA spring actuators connected to the actuation layer with metal snaps. The outer covering is a cotton/poly-blend fabric, graded slightly larger to prevent interference with SMA actuation, and includes pockets to house electronics. The system includes both male and female standard size S.

B. Actuator Locations, Power, and Control Strategies

The compression garment system utilizes NiTi SMA springs to produce compression on various body locations: the torso, shoulders, and upper arms. The SMA actuators were formed into 0.048" outer diameter springs with Flexinol® wire (diameter 0.012", activation temperature 70°C), heat-treated at 450°C for 10 minutes. A total of 12 (female version due to shorter garment length) or 13 (male version) SMA actuators are located on each torso side, 7 on each armband, and 5 on each shoulder area. The actuators are spaced ¾" apart on torso and arms and ½" apart on the shoulders. Each SMA actuator contains a braided outer sheath (¼" Techflex Flexo braid) for heat management, electrical isolation, and to facilitate cyclic resetting of the SMAs. Metal snap connectors were used to form stable electrical connections between actuators and fabric, and to enable the changing of actuator positions when needed. Connections between SMAs and control electronics were formed with wires, managed with fabric/braided sleeves. To allow different compression intensities (low, medium, and high), alternating parallel actuators are activated depending on the desired compression level (specific actuator divisions-Table 1); for each body location, the actuators are distributed into 3 channels, which gives different compression intensities.

The garment actuators were powered by 4 rechargeable LiPo batteries (Tenergy 7.4V 6000mAh 5A). To afford remote control capabilities on the garment, PCBs were designed to house Bluetooth modules (HC05) and electronics, which were connected serially to an Arduino Mega (for parsing Bluetooth signals and relaying digital signals). To activate the garment, current must be passed through the SMA network since SMA shape transformation occurs with heat. The networks are driven by a MOSFET (Vishay Siliconix, N-CH 30V 6A) via Bluetooth signals from a computer, and the specific current flowing through each SMA actuator network is fine-tuned using potentiometers (TT Electronics, ½"). A computer user interface is created with Processing sketch to wirelessly control location, magnitude, and timing of compression.

II. PRELIMINARY GARMENT CHARACTERIZATION

The system weighed 1.2-1.4 kg without batteries (2.35 kg with batteries). Each SMA actuator received around 0.3A of current and actuated on the order of 2-8 seconds. SMAs have a one-way shape memory effect (i.e., they can only compress when powered and must be mechanically re-set). This garment design explores this issue by enclosing the SMAs in a braided sheath, which allowed for the re-setting of the compression (i.e., from tight to loose garment) as the braid expands to its uncompressed length when power is off. The garment re-expanded on the order of 20 seconds. The 3 levels of compression (on a small torso region) were evaluated using Tekscan CONFORMat™, and the heat produced by the SMAs were collected using a FLIR C2™ thermal camera (Fig. 2).

III. CONCLUSION & FUTURE WORK

This paper describes the design and development of garment-based compression technologies that are dynamic, low-mass, and remotely controllable. Immediate study plans involving the developed garment involve: (1) evaluating the objective (e.g. biometric data) and subjective (e.g., user reported responses) effects of compression given varying inputs (intensity, location, duration), and (2) the ability to use compression to modulate affect (since evidence in literature has suggested compression to induce calming effects [1]). Ultimately, this work presents potential for enabling new modes of interaction between users separated by distance, especially in areas such as tele-rehabilitation and social mediated touch. However, there are areas in the garment system that warrant further improvement. The current design requires high power inputs which increases battery bulk and garment weight. Immediate remedial plans involve fine-tuning SMA properties to activate at lower temperatures (to consume less current and generate less heat). Further, three levels of compression intensities in this prototype are applied with a binary system and does not include closed-feedback loop. Incorporating multiple pressure patterns and pressure sensors for continuous data monitoring may lead to more flexible system use design. Finally, the option of a smartphone application alongside a desktop version will also enhance the portability and user-experience of the system.

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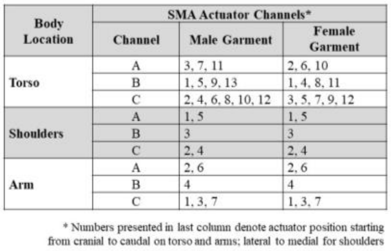
Table 1 (Left). SMA Actuators Distribution. **Figure 2** (Right). Heat (i) and pressure (ii) distributions for low, medium and high compression activation. (A) Low intensity compression; (B) Medium intensity compression; (C) High intensity compression. Note that pressure distributions only involve a small region on lower torso region of the garment due to limited pressure sensor size, and values are raw values (not absolute pressures).



Body Location	SMA Actuator Channels*		
	Channel	Male Garment	Female Garment
Torso	A	3, 7, 11	2, 6, 10
	B	1, 5, 9, 13	1, 4, 8, 11
	C	2, 4, 6, 8, 10, 12	3, 5, 7, 9, 12
Shoulders	A	1, 5	1, 5
	B	3	3
	C	2, 4	2, 4
Arm	A	2, 6	2, 6
	B	4	4
	C	1, 3, 7	1, 3, 7

* Numbers presented in last column denote actuator position starting from cranial to caudal on torso and arms; lateral to medial for shoulders