Iterative Design and Development of Remotely-Controllable, Dynamic Compression Garment for Novel Haptic Experiences

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ABSTRACT

This work encompasses the design and development of garment-based shape memory alloy (SMA) compression technology that is dynamic, low-mass, and remotely controllable. Three garment design iterations are presented, consolidated from past user studies [1], [2], [3]. The designed garment system has potential to serve as a research tool for understanding parameters necessary to create a desired compression haptic experience; for broadening the scope of medical/clinical interventions; as well as for enabling new modes of interaction between users separated by distance, especially in areas such as tele-rehabilitation and social mediated touch.

CCS CONCEPTS

H.1.2. User/Machine Systems: Human factors; H.5.2. Information Interfaces and Presentation: User Interfaces—*Haptic I/O*

KEYWORDS

Compression Feedback; Wearable Haptics; Human Factors; Functional Clothing; Hugging Vest; User Experience

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1 Introduction

Beyond the widespread focus on vibration for haptic systems, researchers have recently begun to appreciate the importance of alternative modes of haptic stimulation. The use of sustained forces on the body (i.e., compression), in particular, offers advantages of being similar to common human behaviors (e.g., a hug), being able to invoke a range of attention capture depending on its compression features, and demanding less user attention than standard vibrotactile approaches [4], [5]. However, current compressive wearables tend to be either passive (e.g., elastic clothing/weighted vests) with little controllability, or inflatables/ pneumatics [6] that are controllable but may be limited in long-term usability due to mobility/bulk (when tethered pumps are required and/or stiffened air pockets). To address these, we identified the design requirements for an ideal active compression garment and investigated wearable actuation technologies incorporating active materials, in this case, shape memory alloys (SMAs) that can repeatedly produce dynamic compression (Fig. 1).

Figure 1: Final garment design (Gen. 3) with SMA actuators

1.1 Shape Memory Alloys (SMAs)

When formed into coil configurations, Nickel-Titanium (NiTi) SMAs are capable of providing large active forces with relatively small form factor (Ø ~ 1.2 mm) that can be used to create dynamic compressions of up to 225 mmHg that scales with an applied current [7]. This feature affords easy garment-integration and facilitates fully enclosed system design without being tethered to an actuation source (e.g., air pump). Further, such SMA coils provide large active displacements that can be differentially adapted to donning/doffing processes (i.e., loose garment when SMA coils are stretched vs. dynamically applied garment compression through coil contraction when heat (or current) is applied). We hence utilize these unique actuator capabilities for designing a targeted compression system that is ultimately dynamic, low-mass, and remotely controllable.

2 Design and Development Process

Our compression garment system was developed through three iterations. Prior to SMA actuator integration, a rapidly-prototyped, passively adjustable garment (***Gen. 1***) was used to inform user experiences and preferences of applied upper-body compression. With the insights gained from this user testing we constructed a dynamic compression garment prototype (***Gen. 2***) to evaluate the feasibility of using garment-integrated SMA coils in applying compression. Lastly, ***Gen. 3*** garments were developed with integrated control electronics and on-board power system, in order to realize a computer-mediated active compression garment system that is simultaneously untethered and remotely controllable.

Throughout our design iterations, we considered the following design requirements for an ideal active compression system:

1. Soft-goods-based system capable of dynamic compression with controllable input levels.
2. Fully enclosed system with on-board power and system controls to afford usability and portability.
3. Self-adjustable with remote actuation capabilities.
4. Unobtrusive form factor with minimal bulk from actuation/control components.
5. Strategic fastening design for easy donning/doffing.
6. Overall garment functionality with appropriate sizing/fit, thermal comfort, and flexibility.
7. Socially acceptable aesthetics and discreet form factor for daily use.

The following sections describe the design and testing of each garment iteration and the associated user study results.

3 Generation 1 – Passive, Adjustable Compression Garment

To gather user feedback prior to SMA actuator integration, we constructed a passively adjustable garment (Gen. 1), optimized for maximal compressibility of the trunk and shoulders with strategically anchored hook-and-loop straps on the canvas-base garment (Fig. 2). To approximate a compression intensity baseline, straps were initially set for a 'conformal-yet-loose' fit on each participant, after which the straps were tightened by 1" on sides.

Figure 2: Gen. 1 passive test garment (from left: front, side, and back views)

3.1 Generation 1 User Study Findings

With Gen. 1, preliminary design insights regarding user comfort and preferences of applied compression were obtained with 5 participants (2M/3F; age range=22-30; mean age=25.4). The following summarizes the user study results; detailed results are presented in Lee et al. [1]:

1. Fabric stiffness greatly influenced the garment's perceived user comfort. Compliant fabrics may provide more comfort but reduce garment-integrated actuator efficiency when actuators are integrated in the future; stiff fabrics may afford more stability but require more precise pressure controls. Fabric selection should balance between structure, compliance, functionality, and comfort.
2. The stark difference between presence and absence of compression stimulus at the bottom of the garment ('edge effect') may negatively affect user's overall comfort. Future garment designs should encourage smoother transition between actuators.
3. Several participants voiced the desire to experience compression on the arms.
4. Despite our initial hope that the adjustable design would mask gender variability, female participants could tell that the garment fit was 'designed for men'. Separate designs for men and women should be created to account for anatomical variances.
5. Many participants felt differences in pressure distribution during torso movements or breathing.
6. Restricted breathing/movement may cause anxiety.
7. Length of the garment should extend to the lower spine, which was a favorable location for many.
8. Shoulder compression preferences were divided between 'two-sides crossed' vs. 'straight', indicating that there may be larger individual differences in perceived comfort of compression than expected (Fig. 3).

Figure 3: Shoulder test conditions (a) Straight, (b) One-side crossed, (c) Two-sides crossed, and (d) Mixed

The strongest theme gathered was the role of movement and breathing while compression is applied. Generally, users wanted more compression on the back, lower spine, and sides, while allowing movement (especially the arms and shoulders), and flexibility in the front for breathing. The feedback obtained from Gen. 1 was used to drive the design process for Gen. 2 garment.

4 Generation 2 – Dynamic Compression using SMA Actuators with Tethered Power Supply

This iteration (Fig. 4A & 4B) focused on integrating NiTi SMA coil actuators (coil outer diameter of 0.048") to provide dynamic upper-body compression. (Coils were made with Flexinol® wire of 0.012" diameter, by Dynalloy, Inc., which was heat-treated at 450°C for 10 minutes and had nominal activation temperature of 70°C.). The garment consists of *inner comfort* and *outer actuation layer*, connected through a front zipper. The inner layer consists of woven canvas front, foam-mesh back (for ventilation and body-contour), and heat insulation side panels below the SMAs, as they actuate using heat (cotton aramid, reflective heat shield for heat management, and Teflon™ with low friction for smooth actuation). The outer actuation layer consists of non-stretch cotton aramid, acting as a muscle layer to which the SMAs are connected. SMAs were spaced 1.0-1.5" apart in a parallel circuit configuration (7 each torso side, 5 each arm, 3 each shoulder), connected to the garment using metal snaps. Fiberglass tape was used to keep SMAs separate. As with Gen. 1, the garment allowed varying compression vectors to be applied (Fig. 5). Shoulder regions 'straight', 'diagonal', and 'mixed' were down-selected from Gen. 1 ('one side crossed' wasn't preferred) and adapted so SMAs do not cross. The shoulder conditions required the torso to be first compressed (anchored) to keep the garment in place.

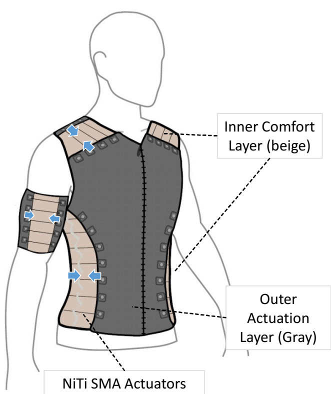

Figure 4A: Active garment illustration indicating different garment layers and SMA actuator locations

Figure 4b: Active garment photos (from left: front, side, and back views)

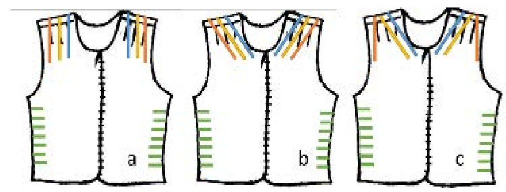

Figure 5: Shoulder test conditions: (a) 'Straight' (oriented vertically); (b) 'Diagonal' (towards chest); and (c) 'Mixed' (outer actuators oriented vertically and inner actuators oriented diagonally towards chest)

After incorporating feedback from Gen. 1 testing, Gen. 2 included the following design features: extended garment length, actuators placed away from garment edges, more compliant fabrics, lowered neckline, and added upper-armbands. As a first-step feasibility study considering gender, a men's garment (size S, 36-inch chest circumference) was designed for Gen. 2 testing.

4.1 Generation 2 User Study Findings

The Gen. 2 garment study included 8 self-identified size-S male participants (age range: 18-27, mean age: 23.5). Detailed results of the subjective effects of compression on the body are presented in Foo et al. [2]. Participant feedback highlights are discussed below.

1. Narrowing the scope of the garment study based on gender (size S males) improved garment fit; six out of eight participants felt the garment was comfortable.
2. Using SMAs improved mobility of the active garment. When activated, the SMAs contract, pulling the passive fabric close, functioning like springs; the garment provides enough resistance to produce compression, but when the user breathes/moves, the spring actuators extend while still providing compression. Some participants felt that mobility was improved with SMAs actuated compared to unactuated.
3. SMAs activate through Joule heating, as such, many subjects felt warmth in the lower back (even though SMAs were not present there). This might be due to the back/spine being a high heat and sweat zone [17] or heat transfer from nearby SMAs on the sides.
4. The 'straight' shoulder condition was the most preferred (6 of 8 subjects). The 'mixed' condition was not preferred by any participants, citing too strong of pressure on the armscye and difficulty breathing (chest compressed).
5. Arm compression preferences were equally split; some felt it had little value and was restrictive (n=4), while others were very satisfied (n=4).
6. The garment system should account for on-board power systems and remote actuation capabilities.
7. The tethering to earth-grounded power systems limits the use potential of the designed item.
8. Controllability of varying compression inputs should be incorporated (intensity, location, and duration).

The Gen. 2 garment proved the feasibility of using SMAs to apply on-body compression. Generally, users were able to detect compression applied and distinguish between different shoulder conditions [2]. However, this generation's garment was tethered to a benchtop power supply, only provided a single compression intensity, used inflexible Teflon™ materials, and supported only a single user size and gender. Hence, we used the insights obtained from user feedback to drive the design process for Gen. 3 garments.

5 Generation 3 – Fully-Untethered, Remote-Controllable SMA Compression Garment

Here, we developed a fully-untethered dynamic garment design with multiple compression intensities, elimination of inflexible Teflon, while supporting both genders. Gen. 3 garments (male and female) consisted of the same two layers (comfort and actuation) as Gen 2 (Fig. 6 A), with an additional outer covering including pockets for electronics (Fig. 6 B-C). Garments were designed to accommodate both genders (M/F, size S). SMAs were housed in braids (Techflex ¼" Flexo) for electrical isolation, heat management, and to support deformation/resetting of the SMAs between cycles. SMAs have a one-way shape memory effect whereby they can only constrict when powered and must be manually deformed/re-set prior to subsequent actuation – the use of braids as a coaxial (external) sheath forms an antagonistic system that allows the SMAs to automatically re-expand when unpowered (due to elastic energy stored in braids as they are compressed during SMA constriction). A total of 13 actuators (male version) or 12 actuators (female version, due to shorter garment length) were located on each torso side, 7 on each armband, and 5 on each shoulder. For shoulders, the compression vectors were further down-selected to only include 'straight' (oriented vertically) and 'diagonal' (towards chest). The SMAs were spaced ¾" apart on the torso and ½" apart on shoulders.

Figure 6: (A) Inner comfort layer and middle actuation layers with integrated SMA actuators on the torso and shoulders; (B) Final men's garment including outer covering and arm bands; (C) Final women's garment

To afford varying compression intensities (low, medium, and high), alternating parallel actuators were activated depending on the desired compression; for each body location, the actuators are distributed into 3 independently-controllable channels, enabling differing compression intensities through selective actuation of 1, 2, or all 3 channels, respectively (Fig. 7-8). Each garment can be actuated with 4 rechargeable LiPo batteries (Tenergy 7.4V, 6000mAh, 5A), enabling untethered operation. Bluetooth modules (HC-05) and associated electronics were connected though serial connection to an Arduino Mega for remote-control capabilities. The SMA networks are MOSFETs-driven (Vishay Siliconix, N-CH 30V 6A) and current flowing through each is fine-tuned using potentiometers (TT Electronics, ½"). A user interface was created with Processing sketch to wirelessly control compression location, intensity, and timing (Fig. 9). The system weighed 1.2-1.4 kg without batteries (2.35 kg with batteries), and each SMA actuator received ~0.3A of current and actuated on the order of 2-8 seconds (relaxing on the order of 20 seconds). Relative spatial distributions of the three compression levels on a small area were measured with Tekscan CONFORMat™ system (Fig. 10).

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.

Figure 7: SMA actuator channel distributions

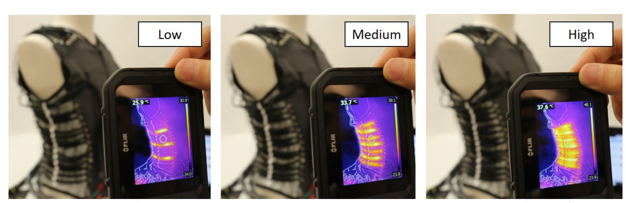

Figure 8: Three compression intensities visualized via a thermal camera; greater pressures are generated by recruiting additional parallel actuators (using Joule heating)

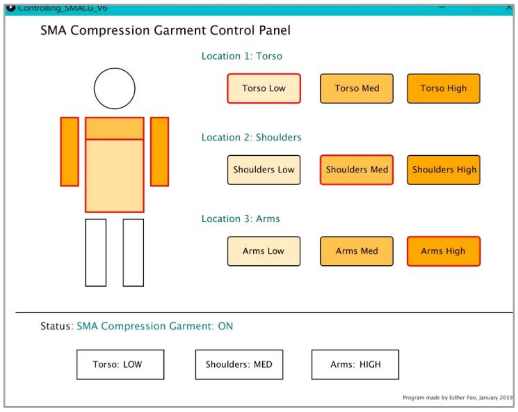

Figure 9: Processing user interface for garment control

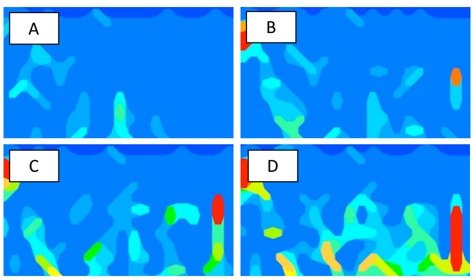

Figure 10: Relative pressure distributions on a mannequin side (right above the hip covering approximately actuators #9-#12 since that area is relatively flat on the body—the reduced body contour in that region allowed better pressure sensor positioning). (A) no, (B) low, (C) medium, and (D) high intensity

5.1 Generation 3 User Study Findings

A larger-scale user study (n=17, 8M/9F, age range: 18-29, mean age: 22.1, size S) was performed using the Gen. 3 garments. The following design insights were gathered (detailed results of subjective user experience are presented in Foo et al. [3]).

1. The relationship between functionality/context and comfort is important. Some participants found the multi-layer construction to be too stiff. Depending on the activity being performed, the snugness could either be beneficial (e.g., provides structured back support like a brace) or restrictive (e.g., limits range of motion). Garment function/use context should be considered for optimal effectiveness.
2. Garment sizing and fit has important influences on the compression experienced by participants, and issues still existed with different gender garments. The garment was ill-fitting on 5 of 17 participants (female: chest area, male: garment length and bottom of armscye). Design strategies such as using alternate materials and incorporating system adjustability should be explored.
3. Different preferences and experiences of compression were observed both between genders and across individuals within a gender group (Fig. 11), with males gravitating towards higher intensity on the torso yet lower shoulder intensity (regardless of its vector). Females tended to favor lower intensities on the torso and the preferred shoulder intensities were more reliant on the vector [3].
4. We found that shoulder compression vectors influence user's perception of varying compression stimuli. Subjects reported that shoulder 'straight' generated more downwards pressure (described as 'someone squeezing/placing hands on their shoulders') than 'diagonal' (described as 'more restrictive'). Understanding the influence of these parameters can improve future system designs/applications.
5. User preferences of compression condition and intensity vary and satisfaction/comfort is largely dependent on the ability to customize settings (see Fig. 11). An ultimate favorite setting across users did not emerge; preferences were unique to each user. Future systems should account for some level of customization depending on its intended use.
6. Thermal management remains a problem. Many participants commented that as the garment use duration was extended, the temperature became overbearing (three subjects enjoyed the heat, describing themselves as 'cold' individuals). A recurring theme still present in Gen. 3 garments was the heat experienced by participants in the lower back, even though no SMAs were located there. Further material/design considerations and placement of nearby SMAs should be explored to mitigate the experience of lower-back heat.

Test Condition			Preference Frequency		
			Males	Females	Total
Torso		Low	♂♂	♀♀♀♀	6
		Medium	♂♂	♀♀	4
		High	♂♂♂♂	♀♀♀	7
Shoulders	Straight	Low	♂♂♂		3
		Medium	♂	♀	2
		High		♀♀♀	3
	Diagonal	Low	♂♂♂	♀♀	5
		Medium			0
		High		♀♀	2
	No shoulders	N/A	♂♂	♀	3
Arms		Low	♂	♀♀	3
		Medium	♂♂	♀♀	4
		High	♂	♀	2
	No Arms	N/A	♂♂♂	♀♀♀♀	7

Figure 11: Compression stimuli individual preferences

6 Future Work

While the compression garment system achieved most of the specified design targets, there are still areas that warrant further investigation. The current prototype is equipped with on-board power systems, but due to the number of actuators, it still requires high power/battery inputs, increasing garment weight. Fine-tuning SMA material properties to lower the activation threshold is a promising avenue to increase thermal comfort and reduce power consumption [8]. Further, this prototype is capable of applying three levels of compression intensities, yet limited to a binary on/off program and does not include closed-loop feedback. To allow maximal system flexibility, several stimuli pattern profiles with finer-tuned compression inputs, as well as pressure/ physiological sensors that capture data should be incorporated. Finally, the development of a phone application for real-time control/modification of compression would enhance system portability and user experience.

7 Conclusion and Broader Impacts

This design statement presents the iterative process towards the design and development of a soft goods system capable of producing dynamic compression on the body. Some major characteristics of the system include:

- Capable of producing computer-mediated, dynamic compression on the body.
- Allows varying compression inputs of location, duration, and intensity.
- Equipped with remote-control capabilities and full-system portability (on-board power and electronics).
- Unobtrusive form factor for enhanced wearability.

The design insights were generated through an iterative process of continually improving system design and added functionality. This work generated insights on the relationship between compression parameters and user experience, as well as the challenges of gender/sizing/fit of wearable haptics. The table below presents a comparison of the three garment iterations. The developed final soft goods system has great potential to be used as a research tool to further understand the effects of upper-body compression on a user; and, ultimately, this system may prove useful in a variety of applications, including enabling new modes of interaction between users separated by distance (e.g., tele-rehabilitation, social mediated touch) as well as new haptic sensations in the area of immersive experiences (e.g., AR/VR).

	GENERATION 1: Passive Controllable Compression	**GENERATION 2: Active SMA Compression (Tethered and Manually Controlled)**	**GENERATION 3 Active SMA Compression (Untethered and Wirelessly Controlled)**
Garment Image			
Objective	Quickly gather user experience feedback on compression stimuli.	Feasibility of integrating SMAs into a garment structure to apply compression on the body.	Towards realizing a fully-contained, remotely-controllable, computer-mediated, dynamic compression system.
System Features	- Rapid prototyping - Adjustable hook-and-loop straps - Lo-fidelity prototype construction - Easily sourced materials	- Application of compression on varying body locations - Utilizes active materials to apply compression on the body	- Application of varying compression location, intensity, and duration - Two-way compression-expansion - Remote-control capabilities - Full system portability - Included male/female gender garments
System Limitations	- Requires manual compression application and adjustment - Utilizes stiff canvas fabrics (low comfort) - Poor fit and comfort - Design/fit men only	- Tethered to a power supply - Only allows a binary on/off compression program - Utilizes inflexible Teflon fabric materials for heat protection - Only had a one-way compression - Design/fit men only	- Issues with thermal comfort (current SMAs require high activation temperatures) - Only provides one compression pattern/rate - Still relatively heavy for everyday use (battery bulk) - Does not include a feedback system

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