User Experiences of Garment-Based Dynamic Compression for Novel Haptic Applications

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ABSTRACT

Compression is a haptic stimulus used in medical interventions (e.g., compression stockings) and has the potential to be integrated into new research areas (e.g., immersive VR experiences, distributed notification mechanisms), yet remains largely understudied. This work investigates the user experience of compression garment technologies that are dynamic, remotely controllable, and low mass, to better address this research gap. Shape memory alloy-based compression garments, capable of creating spatially- and temporally- dynamic on-body compression, were designed and deployed in a user study (n=17, 8M/9F) to understand the effects of compression, and to draw insights for future compression-based applications. The major takeaways are: (1) importance of and sizing/fit, (2) individual/gender preferences and need for customizability, and (3) the relationship between context-specific stimulation and perception.

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; Shape Memory Alloys

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1 Introduction

Beyond the prevalent focus on vibration for wearable haptics, researchers have begun to appreciate the importance of alternative haptic modalities. The use of sustained forces on the body (i.e., compression) offers advantages of resembling common human behaviors (e.g., a hug) and invoking a range of attention depending on compression features, while being less distracting than typical vibrotactile approaches [1], [2]. The garment platform is ideal for generating distributed forces on the body due to its proximity to the body, direct access to large areas, and social ubiquity. Compression wearables are generally either (a) passive (e.g. elastic or weighted clothing), or (b) dynamic inflatables or pneumatics. Some dynamically inflatable solutions remain limited due to immobility and bulk (tethered pumps/air pockets) [3]–[5], but there are portable pneumatic systems that are becoming more readily available. For instance, Tjacket and SqueaseVest are commercially-available compression wear, aimed at providing deep touch pressure to users who experience sensory difficulties [6], [7], however, there are no known compression parameter 'dosages' to generate the claimed positive/calming effects. Huggy Pajama, on the other hand, is a remote hugging garment for social mediated touch [8], [9], but the focus is mostly on parent-child communication. Further, there has been little exploration into using other materials to generate on-body compression. We focus on an alternate approach utilizing an active material, shape memory alloys (SMAs), that can repeatedly and invisibly alter shape when thermally/electrically actuated [10], [11]. SMAs are ideal due to their small form factor and ability to generate controllable compression (up to 225 mmHg) that scales with applied current [12]. In addition, there is a lack of rigorous study of compression stimulation parameters to create desired experiences, which is vital for optimal future compression systems deployment. Hence, we investigate if and how subjective experiences (e.g., preference, comfort) vary among individuals subjected to varying compression stimuli (e.g., location / intensity / duration), through a SMA-integrated compression garment.

2 System Design

This work builds upon work by Foo et al. that demonstrated the feasibility of using SMA actuators in the design of a compression garment [11]. We made the following improvements to our

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Figure 1: System components and design. (A) Comfort layer and actuation layers with SMA actuators on torso / shoulders; (B) Final garments with outer covering and arm bands; (C) Women's garment showing all components (layers

advanced prototype[1] (Fig. 1): (1) replaced inflexible side panel materials; (2) added back ventilation channels for heat management; (3) installed on-board batteries (4 rechargeable Tenergy 7.4V, 6000mAh LiPo batteries) and electronics (HC-05 Bluetooth, HC-05, MOSFET-driven circuitry, Arduino Mega) to eliminate wire tethering, (4) provided multiple compression intensities, (5) added an outer garment covering, and (6) constructed distinct male and female garments for improved fit. The system uses NiTi SMA coils (Ø ~ 1.2 mm [13]) to compress the torso, shoulders, and arms (since they are commonly targeted areas in upper body compression garments). Each actuator has a braided sheath (¼" Techflex Flexo) for electrical isolation, heat management, and facilitation of cyclic resetting of SMAs (to overcome one-way shape memory effects; re-stretching the SMAs when unpowered with elastic energy stored in braids when constricted). Low/Medium/High compression levels were created by differentially actuating parallel actuators (distributed into 3 independently-controllable channels); with higher intensity, more actuators are activated, increasing the compression levels with higher fabric tension (adapted hoop stress formula [12], [13]). The system weighed 1.2-1.4 kg without batteries (2.35 kg with batteries). Each SMA actuator received ~0.3A of current and actuated on the order of 2-8s (relaxing at ~20s). Additional design details are presented in Foo et al. [14].

3 User Study

The within-subjects user study included 17 participants (8M/9F), aged 18-29 (mean=22.1). Compression location (torso/shoulders/arms) and intensity (low/med/high) were studied. Shoulder compression vectors were down-selected from past studies [11] to include 'straight' (oriented vertically) and 'diagonal' (angled inward towards chest). The study was pseudo-randomized; 'torso' with 3 intensities was performed first since shoulder conditions were contingent upon trunk anchoring via torso compression (prevent garment riding up). The participants selected a preferred torso intensity before shoulder compressions were applied, and armbands were added after torso and shoulder preferences were decided. Each body location included 3 compression intensities in random order, giving 12 test conditions (4 locations/orientations x 3 intensities). In each condition, the participants donned the loose-fit, unactuated garment and was provided compression for 1½ minutes (pilot showed users were able to detect and form preferences within a minute) [11]. After the 12 test conditions were done, compression timing, i.e., 'duration' was investigated. The garment (having each user's preferred settings) actuated for a max. of 10 mins (selected as a common duration of compression therapy) [4], [12] by which participants were asked to voice if or when discomfort was felt. The final condition, 'pulsing', involved switching the stimuli on/off every 30 seconds for 3½ minutes instead of constant compression to explore qualitative participant experiences. All participants were seated during the test and completed surveys probing their perception of compression intensities, comfort/discomfort on body locations, and stimulus parameter preferences (specifics of survey metrics will be discussed with their associated results). Subjects were also asked to 'think aloud' during the study and semi-structured interviews were conducted to understand their experience of compression.

4 Results and Discussion

4.1 Perceived Compression Intensities

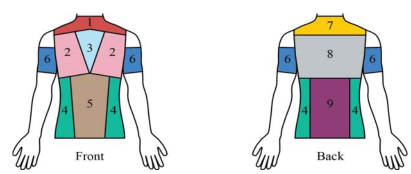

Figure 2. Perceived compression intensity body locations

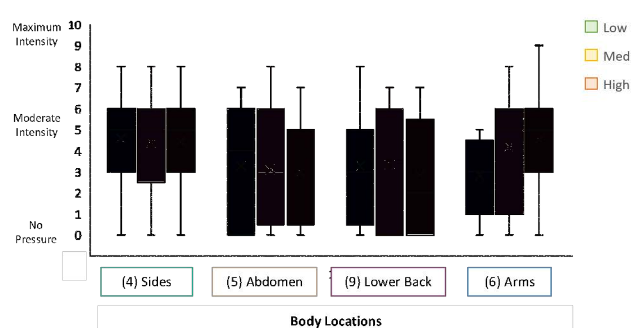

Figure 3. Perceived Pressure Intensities for Torso and

[1] Video presenting compression system design: https://youtu.be/-DWn8G7i-r0

The perceived compression intensities on various body locations (Fig. 2) were collected on a scale of 0 (no pressure) to 10 (max. intensity); subjects were asked to consider 5 as an average hug. As seen in Fig. 3, there were no quantitative increases in perceived intensity for torso areas corresponding to the actual compression. In the lower back, especially, high-intensity compression resulted in lower compression perceptions. Subject comments were nonetheless distinguishable among the 3 levels; low torso compression was described as subtle (n=3) and high torso compression was associated with more pressure/restrictive (n=6)). Three factors may explain this paradox. (i) Many (n=13) commented that compression mostly started or centered on the sides/abdomen (where soft tissues undergo larger volume changes with breathing/movement), possibly drawing attention away from the lower back. (ii) Since the scale was anchored at 5-moderate intensity as being similar to an average hug, the magnitudes of the scale may not be sufficient to tease out the subtle differences between conditions when compared to 'an average hug' (which could be highly variable). (iii) Garment sizing/fit were most challenging in the torso. The garment did not fit well on 5 out of 17 subjects; two females had a snug fit in the torso, one male wore the female-sized garment due to his small stature, and the other two females wore male-sized garment because their torso/chest did not otherwise fit. A clear design insight is the role of garment sizing/fit. The male and female anatomy differ, yet the dissimilarities are under-appreciated—we cannot expect a universally sized system to precisely administer on-body stimuli even when separate garments were made to account for anatomical variances. With compromised fit, garments may shift and present stimuli incorrectly or produce diminished response. In contrast, the arms showed a slightly clearer picture, especially between the low- and high-compressions; 9 subjects mentioned that low level arm compression was felt but subtle, and there was an increasing number of comparisons to a blood pressure (BP) cuff with increasing intensity (n_{low}=1, n_{med}=3, n_{high}=7).

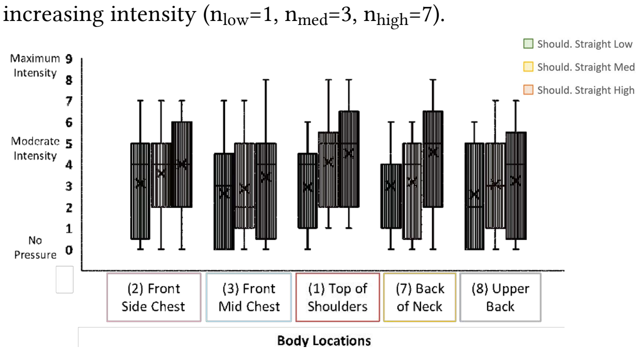

Figure 4. Perceived Intensities for 'Shoulder-Straight'

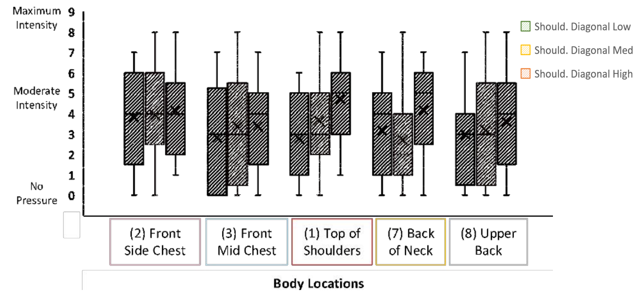

Figure 5. Perceived Intensities for 'Shoulder-Diagonal'

Figs. 4-5 present the perceived compression intensities on the upper chest/back/shoulders, given shoulder compression vectors of 'straight' and 'diagonal'. Generally, the perceived intensities were more distinguished compared to the torso, especially on top of shoulders (both vectors); for high intensity, subjects ($n_{straight}$=7, $n_{diagonal}$=7) voiced clear distinction that it gave the most pressure. Further, majority of the subjects were able to distinguish between compression vectors. For the 'straight' vector conditions, participants felt more compression on the upper back/shoulder blades (n_{low}=3, n_{med}=3, n_{high}=8) or pressing downwards (n=4) while 'diagonal' vector had compression starting and remaining more on the front shoulders / chest (n_{low}=7, n_{med}=6, n_{high}=7). This is reflected in the results, where 'straight-upper back/back of neck' (Fig. 4) and 'diagonal-front mid chest/top of shoulders' (Fig. 5) had clearer distinctions between intensities. This shows that compression vectors played a role in influencing users' physical experiences ('straight'-downwards pressure, 'diagonal'-towards chest) and future applications need an appreciation of the part these variables play.

4.2 Comfort/Discomfort and Preferences

The comfort/discomfort of varying compression stimuli on body locations was investigated using the Comfort Affective Labeled Magnitude (CALM) scale [17]. 'Baseline' was collected prior to wearing garment (no compression); 'duration' condition had subjects exposed to their most preferred stimulus profile for a maximum of 10 mins. Figs. 6,8 show gender-separated means and standard deviation (unidirectional error bars for less clutter); we also determined subjects' preferred stimulus parameters (Fig. 7).

Figure 6. Pressure Comfort of Lower Torso and Arms

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 7. Compression stimulus presentation preference

For the lower torso and arms (Fig. 6), compression generally decreased comfort compared to baseline but remained positive, except the middle/lower back, where compression vs. baseline comfort levels were comparable. (In fact, high compression resulted in higher lower back comfort than baseline for males.) This could mean either that (i) subjects may be inclined towards higher lower back compression, as some (n=5) voiced preference for lower back compression (feels supportive/aids posture); or that (ii) reduced lower back compression perception may correspond to higher system-generated compression intensity (n=13 indicated compressions were on the abdomen/sides; drawing attention away from lower back). Hence, a more 'balanced' compression design should consider moving the actuators slightly towards the back so that the lower back compression can be more evident. These comfort findings lend credence to preference results in Fig. 7; for torso regions, males tended to gravitate to the high torso intensities compared to females. For the arms, we see an inverse compression intensity-comfort relationship; it was likely that being reminded of the BP cuffs (n=11) influenced the subjective comfort levels. Consistent with these results, subjects also generally liked either a low/medium arm compression or no arm compression (Fig. 7). Future design should account for such variances via alternate materials or adjustability.

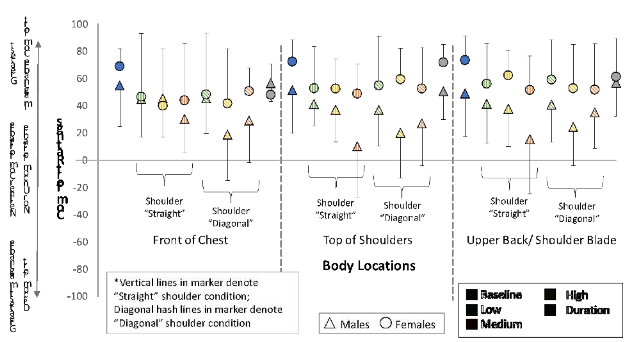

Figure 8. Pressure Comfort of Upper Torso & Shoulders

Fig. 8 presents subjective comfort on upper torso/shoulders with distinct gender differences. Females did not reveal large comfort differences on intensity for different vectors, but male subjects generally found high upper torso/shoulder compressions less comfortable (restricts breathing/movement (n=4)). Males were able to tolerate compression for the 'straight' vector at higher intensities compared to 'diagonal' (generally tolerated 'straight' conditions at medium levels and below, but 'diagonal' was reported as significantly less comfortable at all settings greater than low intensity). With 'straight' vector, participants described feeling compression on the upper back/shoulder blades (n=14), whereas 'diagonal' vector was on the chest, consistent with comments of feeling restricted. As for preferences (Fig. 11), consistent with comfort ratings, almost all males preferred low intensity shoulders (n=2 no shoulders) regardless of vector. In contrast, for females, when 'straight' vector is applied, they preferred high intensities; for 'diagonal', the decision was split. In general, medium shoulder intensity was the less popular choice. With these, we observe the role of gender differences in compression experience, which should be further studied and considered in future compression-based designs/applications.

For all body locations, comfort ratings for 'duration' (Figs. 6 & 8, gray) most closely resemble the ratings of baseline, likely because users were asked to select preferred compression settings. This was supported by user comments, with some (n=4) stating once all parameters were set to their liking, the actuated garment was more comfortable than unactuated. Further, as we probed subjects every minute in 'duration' condition, 11 subjects voiced the tipping point into *slight* discomfort at 8½ mins. All subjects noted the rising temperature while compression remained relatively constant, likely due to the SMA actuator heat and poor breathability of the multi-layer construction.

4.3 Pattern of Compression Stimulus

In the final condition, we briefly explored how different temporal patterns of compression ('constant' vs. 'pulsing' of 30-seconds on-off) affected user experience. Results on preference were close to being evenly split with 8 participants preferring the constant compression, 6 preferred 'pulsing'. Additionally, 3 stated that the preference was situation dependent. Collectively, those who preferred the constant compression noted that it felt secure and was less attention-demanding, yet such constant compression was inviting only with a gradual stimulus ramp-up, since *"sudden change is off-putting"*. In contrast, those who preferred 'pulsing' stated that they liked the renewing sensation and thought that it was more relaxing and akin to a shoulder massage. It was also described as being less intense (i.e., more room for breathing). The 3 subjects who cited situational dependence indicated that the pulsing would be used for stress relief while the constant compression would help one feel 'ready/prepared'. These differing connotations (i.e., constant stimulus provided feelings of active/security; pulsing was associated with relaxation), have interesting implications in future designs since compression patterns could provide contrasting perception/emotions, and we can envision the breadth of functionality they provide (e.g., eliciting diverse sensations in immersive environments: receiving a hug vs. muscle enhancement in gaming).

4.4 Word and Scenario Associations

Participants were also asked to describe their feelings during compression (Fig. 9) and the situations in which the garment may be used. There were three common word categories: (i) calming / relaxing / comforting, (ii) restricted/tight/secure, and (iii) warm. The dichotomy of 'calming' vs. 'restricted' is intriguing, and the

Figure 9. Free word association word cloud

results align with scenario associations; most subjects did associate garment use with emotion-related situations (16 instances) such as stress/anxiety relief, relating to secure/tight connotations., but another prevalent association was medical use (10 instances) such as physical therapy, where 'secure/restricted' fits. This suggest that compression may be received and interpreted differently depending on its use context/expectations. The mapping between language and haptic space (i.e., [3]) should be further explored for active material actuation schemes.

5 Conclusions and Future Work

We designed a wearable system capable of producing dynamic compression inputs of varying location/intensity in an unobtrusive form factor. Using this system as a research tool to understand the effects of upper-body compression, we observed the following themes and implications for future compression garment designs.

1. ***Gender differences and sizing/fit.*** We should not expect a universally-sized system to present on-body stimuli equally (both physically and experientially) across a population, especially with the results suggesting there might be gender differences in compression experience and preferences.

2. ***Compression parameters influenced users' experiences.*** For instance, shoulder 'straight' generated more downwards pressure sensations than 'diagonal' (medial towards chest).

3. ***Individual preferences and need for customizability.*** Preferences vary and satisfaction is largely dependent on an ability to customize settings, hence some level of customization is necessary for individual user satisfaction.

4. ***The relationship between context-specific stimulation and perception.*** Broadly, participants viewed the garment as a potential strategy for emotion regulation or medical use and related it to contrasting terminology groups: calming/relaxing vs. tight/restricted. Further, constant stimulus was related to activeness/security, but pulsing had relaxation connotations. Such groupings suggest a range of possible effects given varied compression parameters and situational differences may call for varying stimuli on different body locations.

The garment design also warrants further improvement in several areas. First, this prototype requires high battery power that increases garment weight. Next steps involve fine-tuning SMA material properties to lower the thermal activation threshold [13] to aid thermal regulation, power consumption, and comfort. Further, while this prototype can apply 3 compression levels, it is limited to a binary on/off program and does not include closed-loop feedback. Incorporating several stimuli pattern profiles with sensors that monitor the on-body pressure and physiological signals will allow more system flexibility. Finally, the option of a phone app. will enhance system portability and use-experience.

Ultimately, this work presents potential for enabling new modes of interaction between users separated by distance (e.g., social mediated touch, tele-rehabilitation) as well as new sensations in the area of immersive (AR/VR) experiences.

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