Dynamic Compression Garments for Sensory Processing Disorder Treatment Using Integrated Active Materials

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Many medical conditions, including sensory processing disorder (SPD), employ compression therapy as a form of treatment. SPD patients often wear weighted or elastic vests to produce compression on the body, which have been shown to have a calming effect on the wearer. Recent advances in compression garment technology incorporate active materials to produce dynamic, low bulk compression garments that can be remotely controlled. In this study, an active compression vest using shape memory alloy (SMA) spring actuators was developed to produce up to 52.5 mmHg compression on a child's torso for SPD applications. The vest prototype incorporated 16 SMA spring actuators (1.25 mm diameter, spring index = 3) that constrict when heated, producing large forces and displacements that can be controlled via an applied current. When power was applied (up to 43.8 W), the prototype vest generated increasing magnitudes of pressure (up to 37.6 mmHg, spatially averaged across the front of the torso) on a representative child-sized form. The average pressure generated was measured up to 71.6% of the modeled pressure, and spatial pressure nonuniformities were observed that can be traced to specific garment architectural features. Although there is no consistent standard in magnitude or distribution of applied force in compression therapy garments, it is clear from comparative benchmarks that the compression produced by this garment exceeds the demands of the target application. This study demonstrates the viability of SMA-based compression garments as an enabling technology for enhancing SPD (and other compression-based) treatment. [DOI: 10.1115/1.4042599]

Keywords: active materials, shape memory alloys, sensory processing disorder, wearable technology, medical devices

1 Background

1.1 Sensory Processing Disorder and Deep Touch Pressure Treatment. Sensory processing disorder (SPD), previously known as sensory integration dysfunction, manifests when the nervous system has difficulty in receiving and processing sensory signals and providing the appropriate motor or behavioral response [1]. This can lead to problems such as motor clumsiness, behavioral problems, anxiety, depression, school failure, and challenges performing many everyday tasks [1]. The condition is prevalent, being estimated to affect 5–16% of children [2,3]. Many individuals on the autism spectrum often suffer from SPD, however, the condition can also manifest separately or in conjunction with other conditions, for instance with attention deficit and hyperactivity disorder [4,5].

In order to cope with sensory processing difficulties (specifically sensory modulation, including over and under-responsivity, as well as tactile defensiveness) some individuals with the disorder seek out deep touch pressure (DTP) [4] and occupational therapists often prescribe the treatment [6,7]. This type of tactile input, also known as swaddle therapy, can be produced when firmly touching, holding, hugging etc. [4].

The effectiveness of DTP as an intervention needs further investigation: some suggest a benefit [4,5,7–14], whereas others found no significant link [15–18]. This inconsistency has many possible causes, but may partly be caused by the lack of standardized protocol used in previous studies [17,19]. Morrison argues that a lack of standardization in treatment may explain the deficiency of definitive evidence in the effectiveness of DTP, and that further research is necessary to determine weight and duration of wear standards [17]. Additionally, inconsistent findings might be related to lack of uniform definitions for critical terms [19] and the application of different theoretic constructs between studies [20]. Inclusion criteria for participants are also inconsistent, which could lead to inconclusive findings [19]. For instance, interventions may be most effective for individuals with higher initial arousal levels, and researchers may see more significant results when using DTP in a context when the participants have higher arousal or anxiety, rather than when they are calm [13,14,21]. Further, DTP treatment outcomes are often subjective, difficult to quantify and not consistent between studies [19,20]. Some researchers argue in favor of reduced stereotypic behavior or increased attention to task as primary indicators of successful intervention [15] while still others argue that relative anxiety level is the most significant parameter by which to judge the effectiveness of a given treatment [4]. In addition, some studies look for only immediate results. For instance, Reichow et al. [15] found that weighted vests did not increase engagement for children with developmental delays and autism in the short term. Long-term effectiveness was not investigated. There is an open debate about the effectiveness of the DTP, including uncertainty regarding both the optimal intervention parameters and metrics to judge effectiveness. In order to resolve these uncertainties, more study of DTP is needed, requiring advancements in technologies designed

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Table 1 Analytical pressure production model inputs and outputs, with typical values presented for a 1 cm wide active sleeve sized for a human thigh

Source	Parameter	Description	DTP vest value
Manufacturing specification	C	SMA spring index (D/d)	3
	d	SMA wire diameter	3.05×10^{-4} m
Cited from literature [31,43]	η	SMA spring packing density	0.9
	G_A	SMA austenite shear modulus	7.5×10^{9} Pa
Experimentally determined	E	Passive fabric Young's modulus	12.9×10^{6} Pa
	L_{F0}	Passive fabric's unstretched length	4.34×10^{-1} m
	L_{S0}	SMA twinned martensite length	1.27×10^{-2} m
	n_a	Number of parallel actuators in the system	16
	r	Object radius (assuming cylinder)	8.8×10^{-2} m
	t	Passive fabric thickness	2.7×10^{-4} m
	w	Passive fabric axial width (i.e., garment height)	0.17 m
Calculated	ΔX_{System}	Unstretched system closure gap = [$2\pi r$ − (other nonfabric structures) − ($L_{F0} + L_{S0}$)]	0.10 m [7×10^{-3} m zipper]
	P_A	Active counter-pressure	7.01×10^{3} Pa [52.5 mmHg]

to provide repeatable, tunable, long-term, and contextually pervasive DTP treatments.

1.2 Current Deep Touch Pressure Compression Garments and Treatments. There are various existing DTP therapy products on the market which are used extensively for SPD treatment. These include nonwearable options such as a roller machine[2] and Temple Grandin's squeeze machine [4]; as well as pneumatic garment options like Snug Vest [22], T-jacket [14], and the Vayu Vest;[3] both weighted vests and blankets; and nonadjustable options, which include tight-fitting compression garments.[4] Other squeezing garments exist that can actuate torso compression for non-SPD applications, such as Huggy Pajama's pneumatic vest [23] and CuteCircuit's HugShirt [24] which both record and send "hugs."

There are several usability and functionality compromises to the existing compression products for DTP therapy. The DTP therapy should be able to meet the user's needs for unobtrusive and noninvasive application of the pressure. The therapy should fit within the user's lifestyle without adding additional stress, unwanted negative social attention, or interrupting the user's daily life. In addition, the product must meet certain DTP functionality requirements, namely the ability to provide a variety of pressure outputs. Providing solely constant pressure becomes a problem because treatment effectiveness can be reduced when individuals acclimate to applied pressure [7,25]. Existing products meet some needs well but are missing on others. For instance, nonwearable products provide a variety of pressures. However, because of their size and weight, they require the user to travel to the product in order to receive DTP therapy. This can be disruptive to the user by limiting their needs-based access to the therapy. Garments offer a solution, as they are portable and wearable. Weighted vests are able to provide a stepped range of pressures. However, they can be limiting in that the user must be sitting when wearing the garment and it must be doffed in order to alleviate or adjust pressure. These vests are also somewhat bulky, which can draw unwanted attention to the wearer. However, weighted vests can be disguised as fashion items (i.e., jean vests). Pneumatic garments can have their pressure adjusted while worn; however, they require a pump and must inflate in order to apply this pressure. This can draw unwanted attention to the wearer. Tight fitting elastic garments can be easily hidden beneath the wearer's clothing. However, these garments are only able to provide one pressure magnitude. They can also be difficult to don. Both pneumatic and elastic garments can be worn during everyday activities without restriction. Existing therapy products provide successful solutions to many problems for individuals with DTP along with some important shortcomings.

Beyond the functional limitations of current DTP garments, there is no clear clinical standard for treatment (and therefore no clear benchmark for designing DTP products). Some guidelines for DTP pressure magnitude and duration exist (enumerated in Table 1), but they are inconsistent and not standardized. For weighted vest and blanket applications, 5% or 10% of the wearer's body weight have been used [15,17]. However, it is unclear over what body area that weight might be applied. By contrast, medical-grade compression garments for other therapeutic purposes can range from 20 to 60 mmHg in pressure, the upper bound of which is acknowledged to be uncomfortable and difficult to don for patients [26,27]. It has been noted that there may be adverse effects to the wearer's health while wearing swimsuits or shape wear applying mean pressures above 25 mmHg [28]. Additionally, it has been found that compression garments worn by burn victim to treat hypertrophic scars are uncomfortable and can cause tissue break down when applying over 40 mmHg [29]. Grandin found that constant or slowly varying pressure was the most soothing and also recommended that the pressure should be applied for at least 5 min [4]. If the pressure remains constant, the wearer can acclimate and the therapy becomes ineffective, suggesting a dynamic option would be preferable [7,25]. Anecdotal evidence suggests that the pressure necessary for treatment may change depending on the time of day (or other circumstances) or might change over time [4]. It is also important in many cases for the wearer to have autonomy over the pressure applied—the DTP treatment should accommodate this need [4]. There are many variables that affect this therapy. Controllable dynamic capabilities and subtle interfaces are both important, but more work should be done to fully understand the requirements and optimize the treatment of SPD.

1.3 Shape Memory Alloys for Compression Garment Actuation. Recent research efforts have explored new compression garment designs using modern technologies, with positive results. These studies have demonstrated that it is possible to make a compression garment that is dynamic, controllable, and form fitting, using integrated active materials [30–33]. This overcomes the usability issues that exist in current compression products. Specifically, garments with shape memory alloy (SMA) springs have been shown to produce controllable counter-pressures by exploiting the shape-changing properties inherent to SMAs [31].

Shape memory alloys, such as NiTi, are a category of active materials that undergo solid-state phase transformation as they are heated (transforming from low-temperature, malleable martensite phase to high temperature, superelastic austenite phase). This

[2]https://www.southpaw.com/steamroller-deluxe.html
[3]http://www.vayuvest.com/
[4]https://funandfunction.com/calm-and-focus/weighted-products.html?gclid=CPmO2tTco80CFZKCaQodJOwBO

phase transformation manifests as a repeatable, macroscale change in shape in the absence of external stress that can be tailored via preprocessing and annealing of raw SMA material [34]. Forming SMA wire into low spring index (spring diameter/wire diameter ∼3) springs—and preprogramming the material such that the memory state is the solid spring (i.e., fully shortened) form—enables repeatable linear actuation strokes capable of producing large (>5*N*) forces and large (>75% reduction in length) displacements in a highly compact (∼1 mm diameter spring) form factor [35].

By integrating SMA springs into the circumference of a garment, the SMA actuation stroke can be exploited to generate increasing amounts of hoop stress in the garment as the SMAs contract (stretching the garment fabric), which causes an increase in pressure if wrapped around an object (or person). As the number of springs increases, so does the total potential pulling force, and thus, the total potential hoop stress and active pressure. Because these actuators trigger as they are heated, they can be effectively controlled through an applied current (which induces Joule heating in the material), and the amount of pressure generated can be modulated by changing the magnitude of the applied current [32]. As a result, SMA-based compression garments can be highly functional (i.e., creating counter-pressures > 225 mmHg), unobtrusive, silent, and remotely controllable (if paired with onboard batteries and a wireless controller), with great potential for applications such as treating SPD [31–33].

1.4 Shape Memory Alloy Garment Applications. There are various garments that have incorporated NiTi SMAs, including a self-adjusting garment for individuals with cerebral palsy [36], mechanical counter pressure space suit applications using SMA springs [30–32], and knitted SMAs stockings to help individuals with a vein disorder [37]. Integration of SMA fibers as knitted textiles have been explored to enable specific shape-change actuation behaviors dependent on the architecture of the textile structure [38,39]. SMA actuators have also been used to create esthetic effects for fashion garments, such as the Skorpions, Kukkia, and Vilkas garments from XS Labs [40,41].

1.5 Research Objective. To address the limitations in current SPD compression garment design, in this investigation, the research team evaluated the ability of an SMA-based active compression vest, designed specifically for DTP/SPD applications, to apply circumferential compression to a child-sized torso. To assess the active garment system, a novel SMA compression vest was designed, modeled, and tested to assess the forces and pressures applied to a representative mannequin torso. The ultimate objective of this research is twofold: to assess the viability of a wearable SMA therapy garment for SPD applications and to develop an active garment system to serve as a research tool to help assess, and standardize, future SPD treatments and pressure testing procedures.

2 Active Compression Garment Design and Modeling

2.1 Shape Memory Alloy Vest Garment Design and Construction. The SMA hug vest developed for this study incorporates NiTi wire (in spring form) as actuators to create compression and is depicted in Fig. 1. To understand the requirements for a DTP garment, the authors surveyed the literature and interviewed several experts and practitioners in the field of occupational therapy:

(1) Patricia Orme, OTR/L
(2) Peggy Martin, Ph.D., OTR/L
(3) Laura Sopeth, OTR/L
(4) Leann Shore, OTD, Med, OTR/L
(5) Jean Bannick, MOTR/L
(6) Andrea Howard, COTA/L
(7) LouAnne Boyd, Ph.D.

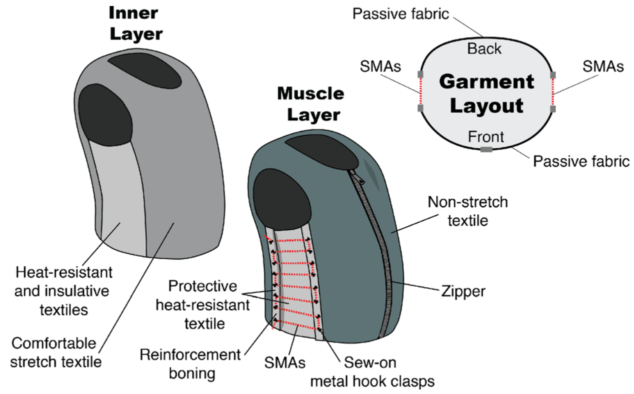

Fig. 1 Shape memory alloy compression garment comprised of an inner comfort layer and outer muscle layer. The SMA wire is processed into a spring and laced through each side of the garment to produce compression.

Using the feedback from therapy practitioners, guidelines from the literature, and a functional clothing design process, initial requirements were outlined for the active garment design. However, there are many aspects to DTP treatment that are not deterministic. These include the magnitude of applied pressure for DTP treatment, if the pressure should be constant or changing, the duration of pressure and time between treatments, and the location of pressure. The autonomy of the wearer, garment sensing, and feedback as well as functional and comfort requirements may also be important variables, however, these require further investigation. Further research should be conducted to more fully outline garment requirements for DTP therapy. DTP initial critical variables and garment requirements that emerged are as follows:

(1) easy donning and doffing (Martin et al. Personal Communications 2017) [42];
(2) fit adjustment created without SMA actuators (to preserve actuation potential);
(3) variable pressure capable of slowly increasing or constant pressure at different magnitudes (Boyd Personal Communication 2016; Orme Personal Communication 2016; Martin et al. Personal Communications 2017), Grandin [4];
(4) Nonobtrusive/social acceptance (Orme Personal Communications 2016) [42];
(5) at least 5 min of pressure [4];
(6) user comfort (e.g., garment sits away from wearer's neck) (Orme Personal Communication 2016; Bannick and Howard Personal Communications 2017);
(7) enough pressure for DTP (specific metrics unknown);
(8) user autonomy (e.g., wearer can self-adjust pressure) [4,19].

The garment has both an inner comfort layer and an outer muscle (actuation) layer, which creates the compression needed to generate DTP. The muscle layer is made from a combination of passive fabric and 16 SMA spring actuators. The inner comfort layer insulates the wearer from SMAs (as they are heated during actuation) and creates a low friction base on top of which the muscle layer moves. This was created by combining a lycra textile, for low friction and comfort, sewn with a aramid and neoprene textiles for insulation and heat resistance. The muscle layer uses a combination of nonstretch, low friction textile, and SMA spring actuators in a laced formation on the left and right sides of the torso. The SMAs were attached to the textile using sew-on metal hooks. This area is structured and reinforced with boning, which helps to evenly distribute pressure generated by the SMAs. A zipper down the front allows for easy donning and doffing of the garment. A schematic of the designed garment along with all the components is shown in Fig. 1. Figure 2 also shows the photograph of the actual garment fitted on the mannequin.

Fig. 2 Photograph of the SMA-actuated compression garment front (left) and side view (right)

To create the actuation regions, on each side of the garment a singular SMA spring (1.25 mm diameter, 53.3 cm length when fully extended) was laced eight times from bottom to top of the garment, spaced 1.9 cm (0.75 in.) apart vertically with a gap of 5.1 cm (2 in.) horizontally. This architecture was repeated on each side of the garment, creating two actuation regions each with eight parallel actuators evenly spaced (for a total of 16 actuators). These springs acted as electrical resistors (that heat when exposed to current), and each spring comprised an independent circuit capable of producing compression when powered. For this study, the garment was powered by an external power supply and both springs were actuated simultaneously. The weight of the garment was about 0.4–0.6 kg comprising only the textiles and the actuators.

2.2 Active Pressure Modeling. Previous work [30] has shown that it is possible to predict the pressure generated by an active garment with integrated SMA actuators, based on 12 system parameters. Specifically, active pressure can be calculated as follows (see Table 1 for detailed breakdown and description of model parameters):

$$P_A = \frac{\Delta X_{\text{System}} G_A d^2 n_a E t}{r(G_A d^2 n_a L_{F0} + 8EwtC^3 \eta L_{S0})} \quad (1)$$

The pressure production model is based on several assumptions, which affect the overall accuracy of its predictive power. Assumptions include:

(1) Pressure is generated on a rigid, cylindrical object.
(2) Friction is negligible and garment is structurally uniform (i.e., tension is generated uniformly around the circumference)
(3) SMA and passive fabric have linear stress–strain behavior (i.e., can be modeled as linear springs).
(4) SMAs are fully transformed (i.e., model only predicts maximum possible pressure generated).

Shape memory alloy actuators have been shown to be highly linear [31], and the passive fabric selected for the DTP vest prototype (satin weave textile reinforced with fusible interfacing) was tested using an Instron tensile test apparatus and shown to be highly linear ($R^2 > 0.95$) for strains up to 6%. These properties conform well to model assumptions. Friction properties, garment structure, and mannequin geometry are more difficult parameters to control (and in reality will necessarily deviate from the idealized model assumptions). Deviations in these assumptions will affect model accuracy.

To model the DTP vest system developed in this study, values for each of the 12 system parameters were estimated from a variety of sources, or measured directly (enumerated in Table 1). Specifically, values were sourced in one of the following ways:

(1) Known a priori from SMA actuator manufacturing process
  (a) SMA spring index (C), and SMA wire diameter (d)
(2) Experimentally determined specifically for DTP vest prototype
  (a) passive fabric Young's modulus (E), fabric unstretched length (L_{F0}), SMA twinned-martensite length (L_{S0}), number of parallel actuators (n_a), average object radius (r), fabric thickness (t), and fabric width (w)
(3) Cited from previous experiments/literature
  (a) SMA austenite shear modulus (G_A) and SMA spring packing density (η) [31,43]
(4) Calculated/derived from other parameters
  (a) Unstretched system closure gap (ΔX_{System}).

Based on the estimated system parameters, the active pressure model predicts that the DTP prototype system will generate 7.01 kPa [52.5 mmHg]. Optimum DTP metrics still need to be established; however, other clinical compression garment metrics find the predicted measure of 52.5 mmHg to be within (or above) acceptable range: Teng and Chou experimentally measured burn compression garments and found them to vary between 20 and 40 mmHg [26], and Brennan et al. quote elastic garments between 30 and 60 mmHg [27]. Since these applications of compressive garments are more tolerant of patient discomfort and mobility restriction (both of which have been reported at these levels of compression), it is likely that a benchmark for DTP would be lower than that of burn recovery or other circulatory conditions. Based on these metrics, the SMA garment system should produce the required pressure output for DTP treatment.

2.3 Shape Memory Alloy Power, Length, and Time. Because the ultimate objective of this research effort is to assess the feasibility of SMA-based compression systems to provide dynamic compression for DTP applications, the relationship between SMA spring length, applied power, and actuation time first needs to be better understood to establish the feasible limits in terms of cycle time and power consumption. Several SMA actuators were manufactured using custom equipment at the UMN Wearable Technology Laboratory for both performance characterization/validation testing and prototype creation. Length–voltage–time tests were conducted to assess response time as a function of length and applied power. In each test, a predetermined voltage was applied to an extended (i.e., de-twinned) actuator of a given length, and response time (measured in seconds to complete total constriction) was measured. Each test condition was repeated three times, and the results are shown in Fig. 3. While the voltage is the electrical parameter that was controlled and changed for this test, we also report the current in the SMA as a function of its length and applied voltage in Table 2. The missing values in the table correspond to either very slow response time (for very large lengths and/or small voltages) which made measurements very difficult or for very fast response time (for smaller lengths and/or higher voltages) which could lead to excessive heating and eventual damage of the SMA sample.

The results of this test are consistent with expectations (see Fig. 3): as actuator length increases, response times are slower for a fixed voltage. Beyond a critical length (which varies for a fixed power input), response times slow nonlinearly (trending to zero response—or infinite response time). This suggests that beyond a certain threshold the applied power is insufficient to induce heating above the critical SMA activation temperatures. Data are represented with ±1 SD error bars in both the X and Y axis, when available. Deviation in actuation time tends to increase with SMA length (due to increasing heat transfer variance). These findings point toward a reduction in system actuator used in order to reduce actuation time and power consumption. Alternatively, larger power use could also achieve the desired actuation time if a longer length of SMA spring is required.

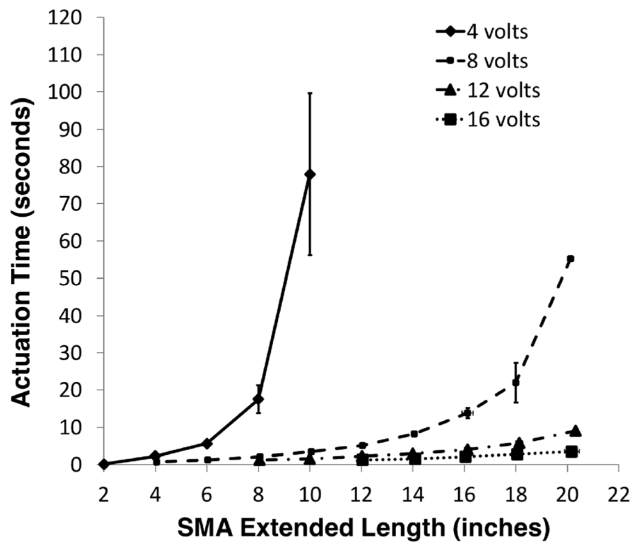

Fig. 3 Depicts SMA actuator power, length, and time plot

3 Methods

3.1 Experiment Design. To characterize the pressure generation capabilities of the active DTP vest system, the vest was donned on a 3T child-sized mannequin, and pressure data were collected as a function of spatial location and time for a variety of power inputs. To collect the pressure data, a Tekscan CONFORMat 5330 pressure sensor (471 mm × 471 mm active sensing region, 1024 sensing elements, 0.5 sensels/cm^2, 34 kPa maximum pressure) was centered on the mannequin (underneath the vest system) and was secured using adhesive tape. This is shown schematically in Fig. 4. Although the sensor is one of the more 3D-conformable methods available for collecting surface pressure measurements, conforming a planar measurement device to the topography of the body is a challenge. Because of sensor constraints such as overlaps, wrinkles, and the exacerbation of these factors in body areas with more extreme curvature (such as, in the case of the mannequin used in this test, the more extreme concavity at the lower back), data were collected only on the front and sides of the garment. The area falling within the front and sides of the garment (as shown in two dimensions in Fig. 4 contained 11 × 25 sensors (for a total of 275 data points). For each time instant, the pressure measured by each sensor in the array was captured, and the average pressure across the entire array was calculated.

A baseline pressure measurement was collected from the mannequin-mounted sensor before the garment was donned, and this bias was removed from the garment pressure data. The garment was then donned on top of the Tekscan sensor and fastened as it would be worn on the body. All data were collected without repositioning the sensor or the garment after this initial donning procedure.

The test procedure characterized the SMA DTP vest at various power inputs in order to determine pressure output. In each of the trials, data were collected for 30 s at a 0 V. The power was then manually applied via a tethered power supply to both actuation regions simultaneously for a period of 5 min each at 10 V per side (0.566 A, 5.81 W), 15 V per side (0.857 A, 12.85 W), and 20 V per side (1.096 A, 21.92 W). After this, the power was shut off and the vest was allowed to passively cool down. This procedure was repeated five times. Voltage was adjusted manually at each time interval. Current (A) was recorded at each power level for each test in order to calculate

Table 2 Variation of current as function of applied voltage (rows) and SMA length (columns)

	Length (→)									
Voltage (↓)	20 in.	18 in.	16 in.	14 in.	12 in.	10 in.	8 in.	6 in.	4 in.	2 in.
4 V	N/A	N/A	N/A	N/A	N/A	0.38 A	0.49 A	0.67 A	0.98 A	1.84 A
8 V	0.375 A	0.45 A	0.51 A	0.6 A	0.68 A	0.82 A	1.04 A	1.39 A	2.04 A	N/A
12 V	0.62 A	0.73 A	0.79 A	0.89 A	1.05 A	1.40 A	1.72 A	N/A	N/A	N/A
16 V	0.85 A	0.95 A	1.07 A	1.32 A	1.51 A	N/A	N/A	N/A	N/A	N/A

Note: The lengths are reported in inches, voltages in Volts, and current in Amperes. Note that values reported as N/A correspond to unmeasurable values for very slow response time (for long lengths and low voltages toward upper left corner) or very fast response time (for larger voltages and small lengths toward lower right corner).

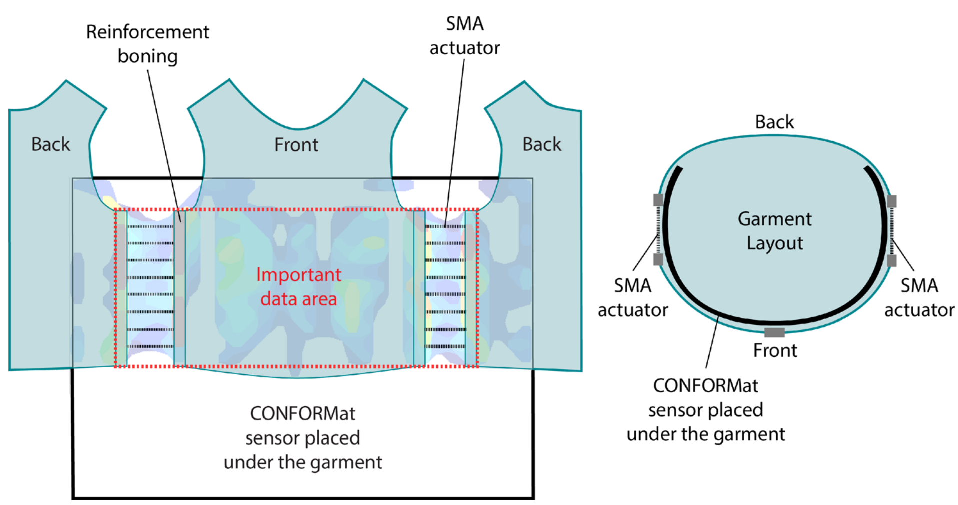

Fig. 4 Tekscan CONFORMat sensor and garment placement for data collection

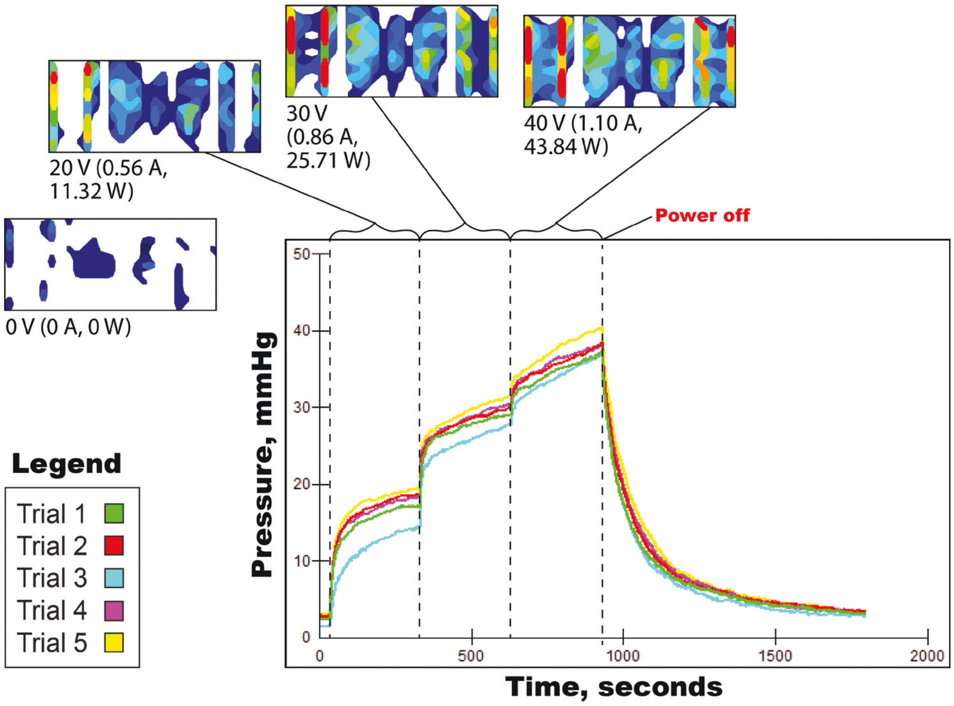

Fig. 5 Data showing average pressure, mmHg, over time. Average pressure is defined as the average force applied over an area. Power was applied with increased intensity at fixed time intervals of 5 min after an initial period of 30 s. Data show that the average pressure output increased with power input.

total power (*W*). To determine nominal pressure for each power step, the average pressure for each sensor in the array was calculated for the last 60 s of activation for all five samples. Then, the average of these samples was calculated. The average standard deviation was calculated spatially.

4 Results

Figure 5 presents the average of the pressures measured by all sensors in the recorded window for each time sample in each of the five successive trials (separate trials shown in differing colors). The callout images show representative samples of the pressure distribution throughout the array for each power step in the test procedure. As expected, with increase in the power input the average pressure output for all five tests increases. When the power source is shut down, the pressure gradually decays to the initial value as the garment cools.

Figure 6 illustrates the difference in pressure measured by the CONFORMat sensor array when the vest is powered off (when the body experiences only the force of the passive garment) and at full power (when the body experiences the force generated by the SMA actuators powered at 20 V (1.096 A, 21.92 W) on each side). Spatial distribution of pressure in these two conditions is also illustrated. Garment structures (e.g., SMA actuators, boning, etc.) are visible in the pressure distribution, as they create local nonuniformities in the pressure field.

Figure 7 presents average pressure generated by the garment as a function of applied total power (i.e., including both sides of the

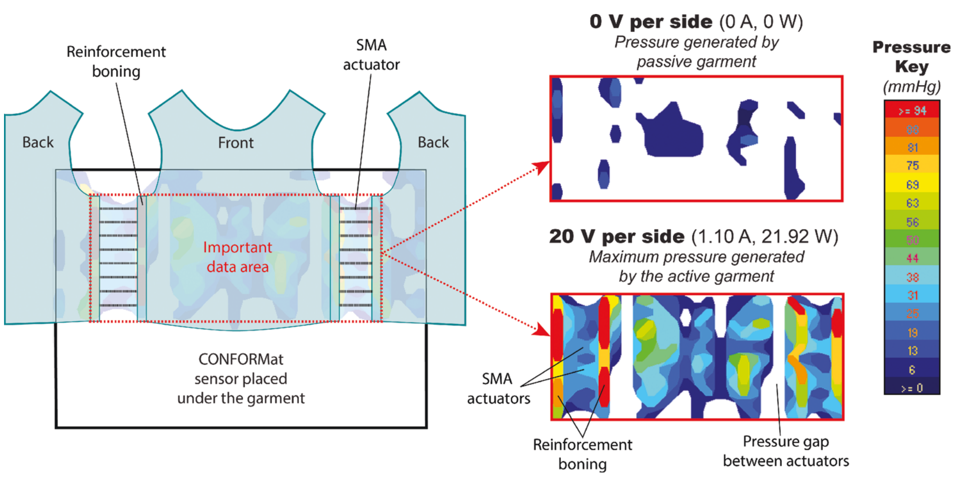

Fig. 6 Tekscan CONFORMat sensor, garment placement (left), and corresponding pressure maps (right) comparing output with no applied power and max power (20 V, 1.10 A, 21.92 W). The temperature bar corresponds to pressure measures in mmHg depicted in the pressure map.

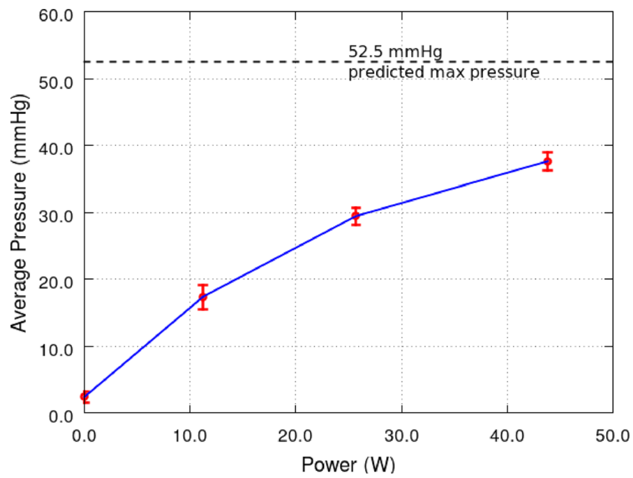

Fig. 7 Depicts the average pressure output (mmHg) from all five samples of the average of the last 60 s of total power input (including both sides of the garments). Standard deviation of pressure output is also depicted. The horizontal line represents the predicted maximum pressure output of 52.5 mmHg.

garment). As power increases, so does average pressure generated, to a maximum of 37.6 mmHg at 43.8 W. For comparison, the maximum predicted pressure based on the validated SMA garment model is 52.5 mmHg (last row in Table 1). We see that the prototype garment generated 71.6% of maximum predicted pressure at the highest power setting tested.

5 Discussion

The SMA garment pressure output increased with power input; however, some variation in spatial distribution occurred, consistent with the unequal circumferential distribution observed in previous SMA compression garment tests [32]. Nonuniform pressure distributions can be caused by a variety of sources: the contraction force is localized (laterally on either side of the torso), causing adjacent areas to be more highly stretched than far-away regions; the interface between layers is not free of frictional drag, causing additional unequal stretching of the garment materials; and the garment is heterogeneous in terms of its construction (with varying surface finishes and localized hard/soft regions), causing localized pressure "hot-spots" and voids. These features can be clearly seen in Fig. 6: there are points of high pressure corresponding to the SMA actuators themselves and the boning structures in the garment, and there are also visible voids to either side of the SMA actuator. This is likely formed because the passive textile is held away from the form by the insulative layer below the SMA springs, and the boundary of the insulative layer creates a local discontinuity in fabric conformance to the underlying surface. Adding padding or fill in this area to translate force to the body might produce a more even distribution of pressure. Finally, across the front torso (the middle of the pressure map), there is also a slight variation in pressure distribution. This is likely caused by changes in the radius of curvature of the mannequin form, which would create varying pressures for a fixed circumferential tension.

A more even distribution is in theory preferable [4]; however, in practice, the effect of pressure distribution is unknown. The design of many existing products does not permit even pressure on all areas of the body. Weighted vests, for example, distribute force mainly over the shoulder area. A benefit of garment-integrated SMA actuators is the ability to adjust pressure location and intensity unobtrusively without doffing the garment. This could help to provide dynamic and adjustable DTP therapy treatments. This is especially true if actuation regions in the garment are designed to be independent circuits, enabling localized (or sequenced) dynamic compression profiles.

The garment produced 71.6% of maximum predicted pressure. This discrepancy is likely attributable to one (or more) violations of the underlying assumptions of the pressure production model: the mannequin form was not perfectly cylindrical; the SMA actuator output may not have been maximized (i.e., the actuators were not fully transformed even at 43.8 W); the garment was heterogeneous in construction (which as previously discussed, caused localized distortions in the pressure field); and the garment was not frictionless.

6 Limitations and Future Work

As with many new therapeutic technologies, the accuracy and specificity of this device exceed current clinical tools, therefore, there is no established precise reference target with which to evaluate the success of the new method. However, using benchmarks from applications with more extreme compression requirements (such as compression garments from other clinical domains [25,26]), it is clear that the garment discussed here is capable of providing compressive forces that are likely to far exceed those typically used in DTP treatments. Another study is necessary to more clearly outline the requirements, including pressure magnitude and distribution, for DTP therapy. This is critical in order to prevent discomfort and avoid any unsafe over application of pressure to the wearer. Once requirement metrics have been determined the garment should be adjusted, either be reducing the amount of SMA used, reducing the power applied or by optimizing the SMA manufacturing procedures. This could be accomplished via alternative base SMA wires and optimizing annealing temperatures and procedures.

Shape memory alloy-activated compression garments are able to produce dynamic compression in a low profile form factor. However, they do require a power source and inherently generate heat. The garment used in this study was cooled through air convection only. In the future, the temperature changes inside and outside the garment upon activation of the SMA actuators should be recorded. Heat should be reduced and managed through utilizing more efficient SMAs and optimizing garment insulation. In addition to these passive techniques, we could also consider active cooling, for example, through liquid cooling.

Further, the measurement of normal forces on the body surface is a complex challenge, for which there is no ideally suited method. In this study, the best-fit technology available was used, but limitations to the method prevented measurement of pressures applied to the dorsal surface of the mannequin. To effectively measure normal forces over the full topography of the body, it would be necessary to achieve either a more fully 3D conformable force measurement device or a custom-fit force measurement platform. As observed in the results, the nonuniform mechanics of the garment structure (which integrates rigid and flexible elements) as well as the nonuniform distribution of frictional forces prevented an even distribution of pressure over the body surface. Additionally, it is possible that industry calibration is not optimal for on body pressure measurement [44]. Future work aims to develop a more ideal method for calibrating Tekscan, Inc.'s, CONFORMat sensor for measuring pressure on the body.

The system developed and tested in this investigation was powered manually, using externally supplied power. A superior architecture would incorporate onboard power (e.g., batteries) and a wireless controller, enabling real-time, wireless, untethered operation. In addition to this, we can consider design with independent SMA actuator circuits. This would allow for introducing a fine-tuned spatial distribution of pressure application in accordance with the complex topography of the human body.

Finally, the experimental protocol implemented here relies on a rigid mannequin in place of a human body. The mannequin surface does not approximate the mechanics of the body, and therefore, there are likely to be inconsistencies, particularly in the distribution of force over the body surface. These factors are also likely to change between individuals, as individual anthropometry and body topography is highly variable [45]. Further, this vest would be used extensively over time; however, this study has not assessed the degradation of the SMAs or textile through periodic wear. A preliminary study on the degradation of SMA actuator performance over its lifetime [43] has evaluated the loss in active force due to periodic activation. It was found that design strategies which try to minimize active stroke length are less susceptible to periodic degradation in performance. Using a more accurate sizing measurement efficient actuator designs can be incorporated. However, this should be further investigated.

7 Conclusions

Based on the results obtained in this study, active DTP garments incorporating SMA actuators present a viable alternative to existing DTP therapy garments, with exciting potential for both precise control of applied pressures and the ability to present dynamic pressure localization and intensity regimens. The SMA vest approach is an unobtrusive, dynamic option, which has the direct capability to be activated remotely via Bluetooth LE, as demonstrated in Ref. [33]. This allows the wearer to self-adjust and overcome desensitization from pressure, as well as allowing occupational therapists or caregivers to prescribe a dynamic sensory diet that can be actuated unobtrusively and remotely (enabling a new paradigm of tele-rehabilitation or treatment). Beyond dynamic control and unobtrusive actuation, many of the other requirements and parameters for optimal DTP treatment are not well understood (due in no small part to the limitations of current actuation technologies) [17]. A more in depth investigation of DTP treatment parameters should be conducted. Additionally, the SMA vest has significant potential as a research tool to evaluate and standardize these DTP treatments by providing more advanced dynamic and controllable capabilities. Pressure distribution over the body surface and its impact on treatment success are high-potential areas for future exploration, in parallel with the evaluation of the effectiveness of dynamic treatments with human subjects. Finally, as compression therapy is used to treat a variety of medical conditions beyond SPD (e.g., diabetes, lymphedema, burns, etc.), the technology developed for this study has widespread clinical potential that warrants further investigation.

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