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ACTIVE-CONTRACTING VARIABLE-STIFFNESS FABRICS FOR SELF-FITTING WEARABLES

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Abstract

Self-fitting is the ability of a wearable, garment or body-mounted object to recover the exact shape and size of the human body. Self-fitting is highly desirable for wearable applications, ranging from medical and recreational health monitoring to wearable robotics and haptic feedback, because it enables complex devices to achieve accurate body proximity, which is often required for functionality. While garments designed with compliant fabrics can easily accomplish accurate fit for a range of body shapes and sizes, integrated actuators and sensors require fabric stiffness to prevent drift and deflection from the body surface. This paper merges smart materials and structures research with anthropometric analysis and functional apparel methodologies to present a novel, functionally gradient self-fitting garment designed to address the challenge of achieving accurate individual and population fit. This fully functional garment, constructed with contractile SMA knitted actuator fabrics, exhibits tunable %-actuation contractions between 4-50%, exerts minimal on-body pressure (1333 Pa or 10 mmHg), and can be designed to actuate fully self-powered with body heat. The primary challenge in the development of the proposed garment is to design a functionally gradient system that does not exert significant pressure on part of the leg and/or remain oversized in others. Our research presents a new methodology for the design of contractile SMA knitted actuator garments, describes the manufacture of such self-fitting garments, and concludes with an experimental analysis of the garment performance evaluated through three-dimensional marker tracking.

Keywords

shape memory alloy; wearable; functional fabric; self-fitting; knitted actuator

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1 INTRODUCTION

The success of advanced functional apparel, such as wearable technologies, is dependent on fit, which is defined as the dimensional difference between a wearable, garment, or body-mounted object and the human body [1]. Advanced functional apparel enhances or augments user capabilities through functions such as actuation, sensing, energy harvesting, and communication, which enable the wearable to provide physical assistance (e.g. wearable robots [2]), health maintenance (e.g. smart compression stockings [3]), health monitoring (e.g. wearable medical sensors [4]) or information delivery (e.g. haptic garments [5]).

Accurate fit (i.e. when garment dimensions are equal to the body dimensions) enables wearable actuators to transmit forces effectively from the wearable to the body and, likewise, enables sensors to monitor body function with minimal error by increasing placement accuracy and reducing drift. Due to the complex, variable, and dynamic anthropometrics of the human body, the design of non-compliant, fitted garments thus far requires the integration of closures, such as lacing, hooks, and snaps. These closures complicate the don/doff procedure and force a design trade-off between adjustability/fitting requirements and functional actuation/sensing requirements. Self-fitting wearables can bypass these limitations by providing accurate fit without the addition of bulky and complicated closures. Additionally, active-contracting variable-stiffness fabrics stiffen upon actuation, enabling a large, continuous, and stiff surface upon which actuators and sensors can be mounted to the body. The design and development of active-contracting, variable-stiffness fabrics will reduce the design complexity of fitted wearables, improve consumer usability, and enable accurate fit for a large consumer population.

Active materials such as shape memory alloys (SMA) [6], shape memory polymers (SMP) [7], and carbon-nanotubes [8] have been previously integrated into compliant knitted architectures to provide large actuation contractions in response to thermal or electrical inputs. Contractile SMA knitted actuators accomplish up to 50% actuation contractions [6], are biocompatible [9], and their geometric design parameters have been correlated to macroscopic performance metrics [10]. The active contractile mechanism of SMA knitted actuators is based on geometrically leveraging the shape memory effect (SME) of SMA, which is used as the active monofilament in the knit manufacturing process. A reversible phase transformation between an austenite and martensite phase is initiated by heating above and below phase transformation temperatures. The mechanical properties, such as the effective material stiffness, are dependent on the phase and can therefore be controlled through changes in temperature.

This research presents the design, manufacture, and testing of a proof-of-concept, fully-functional, self-fitting, self-stiffening garment design. By merging anthropometric data and apparel design methodologies with smart materials and structures research, we propose a novel, functionally gradient garment designed to address the challenge of achieving accurate individual and population fit. We present a brief background of anthropometry followed by SMA knitted actuator research to lay the groundwork for new, actuating garment design methodologies. This case study covers anthropometric analysis, definition of garment

contractile requirements, SMA knit actuator selection processes, and full-garment design and manufacture. A final proof-of-concept prototype was validated through three-dimensional marker tracking, which was used to assess the contractile ability and the quality of fit post self-fitting.

2 ANTHROPOMETRY & GARMENT FIT

Garment fit is defined as the relationship between garment dimensions and body dimensions [1]; consequently, the design of a self-fitting garment necessitates an investigation of the garment-body interface. Anthropometry, or the study of the size and shape of the human body [12], provides the foundation for fit analysis. The following sections map the challenges of achieving fit with current anthropometric resources and apparel design methodologies.

2.1 ANTHROPOMETRY OF THE LOWER EXTREMITIES

While garments are ubiquitous and methods for producing mass garments are well established, fit challenges are pervasive in the consumer market. Fit challenges are further magnified in the design and distribution of advanced functional apparel [14]. As shown in Figure 1, using anthropometrics as the basis of garment patterns is a challenge in terms of intra- and inter-subject variability. Cross-sections taken from CAESAR body scans show that the human leg is highly irregular in form, specifically, not cylindrical, from the ankle to the knee. Furthermore, these non-cylindrical cross-sections are not consistent across the population. Common measured body dimensions (e.g. lengths, circumferences) available in most anthropometric databases used in the apparel industry (e.g. SizeUSA [13]) do not provide topographical or morphological data. Consequently, apparel designers make stylish simplifications to body shape and size that are discussed further in Section 2.2. Advanced databases (e.g. ANSUR II [15], CAESAR [11]) incorporate three-dimensional data to enable complex analysis of body volume and morphology; however, body scanning is rarely used in the industrial production of garments because the technology is time-consuming and costly [14]. New methods of automation that enable rapid response need to be conceptualized before body-scanning can enable mass-customization of wearables. [16].

Additionally, the dimensional variability within the population is complex without considering topographical differences [17]. As shown in Figure 2, the apparel industry generally achieves population fit by determining correlations between key body dimensions. These key dimensions are determined through statistical methods, such as principal component analysis (PCA), cluster analysis, or decision tree analysis [18]. Even amongst dimensions with a high correlation (hip dimensions, waist dimensions; $r = 0.89$) [19], technical garment designers are only able to pattern garments to fit a small portion of the population, as depicted by the solid-line, boxed size categories (e.g. small, medium, large, etc.) in Figure 2. The unboxed circles in Figure 2 represent the vast portion of the population that remains unaccommodated, or unfit by the identified size categories. Strategies to improve fit for an individual as well as for a population are discussed in the following section.

2.2 GARMENT FIT

To accommodate anthropometric variability, apparel designers traditionally take one of four approaches. (1) Garments can be designed with compliant fabrics using elastane fibers such as in leggings or leotards. These stretch garments are generally designed with undersized dimensions, called negative ease, so that the garment stretches around the body to achieve a close fit in each size group. The range of dimensional variability that can be accommodated in each size group is dependent on the strain properties of the fabric chosen. (2) Another method is to design garments with non-compliant fabrics and produce a large number of sizes; however, this option is prohibitively complex in terms of both production and purchasing logistics. (3) A frequently used alternative is to increase garment dimensions so that the garment is slightly oversized. The amount of added garment dimension, called positive ease, determines the amount of anthropometric dimensional variability a garment can accommodate. Consequently, oversized t-shirts designed in three sizes may fit a larger portion of the population than a fitted dress shirt in six sizes due to the amount of garment ease that is aesthetically desired in that garment. (4) Another, frequently used alternative is to incorporate adjustable closures (e.g. lacing, hooks, snaps) into a non-compliant or limited-compliance garment [17]. While all approaches are suitable for general consumer garments with only mobility, comfort, and aesthetic requirements, garments with enhanced functionality (e.g. wearables with actuators or sensors) often require complex size-adjustability mechanisms to achieve a close fit when garment stiffness is required [17].

In addition to enabling adjustability, closures are critical design features to facilitate don/doff without garment dimensional compliance or positive garment ease. As shown in Figure 3, while the ankle opening of a pair of stretch leggings can strain as the foot passes through (Fig. 3C), a pair of non-compliant dress trousers must be designed with added dimension, called positive ease, to enable don/doff (Fig. 3A). If a pair of trousers are designed to fit tightly around the ankle, there must also be a side closure (e.g. zipper, snaps) that can be released as the foot passes through and refastened to achieve fit (Fig. 3B).

Alternatively, we propose the use of active-contracting, variable-stiffness fabrics as a new design approach to achieve fit and stiffness without the use of closures. As shown in Figure 4, the ideal design is compliant and oversized in circumference until the garment has been donned. Once around the body, the garment contracts and stiffens fully self-powered with body heat. Percent actuation contraction is designed to achieve fitting to the anthropometry while generated pressures from contraction never surpass 10 mmHg (1333 Pa), which is common garment pressure (e.g. socks) and below minimum medical pressures, which start at 18 mmHg (2400 Pa) [20].

3 SMA KNITTED ACTUATOR FABRICS

Shape memory alloy (SMA) knitted actuator fabrics enable variable-stiffness and contractile functionalities. The hierarchical nature of knitted architectures provides design parameters on various scales (macro-, meso-, microscale), which can be tailored to accomplish desired actuator properties [21]. This section introduces basic SMA material properties, as well as

the, architecture, geometry, functionality, and performance of contractile SMA knitted actuators.

3.1 SMA MATERIAL PROPERTIES

Shape memory alloys (SMA) are multifunctional materials that exhibit unique crystallographic effects resulting in significant changes of the material stiffness and enabling the recovery of large inelastic strains ($\approx 8\%$) [22]. This behavior stems from reversible phase transformations between a higher-stiffness austenite phase and a low-stiffness martensite phase, which are dependent on the temperature, stresses and strains of the SMA material. Depending on the thermal and mechanical loading path, SMAs accomplish two desirable behaviors, the shape memory effect and superelasticity. Superelasticity is a stress-induced phase transformation ($A \rightarrow M$) from austenite (A) to martensite (M) that occurs under constant temperature conditions above the material's austenite finish temperature (A_f) and significantly reduces the material stiffness. The shape memory effect is a temperature-induced phase transformation ($M \rightarrow A$) that allows the recovery of large deformations that occur at a temperature below the martensite finish temperature (M_f) through heating of the material above its austenite finish temperature. [23]

SMAs are most commonly binary alloys of Nickel and Titanium. The characteristic phase transformation temperatures can be designed through adjustments of the alloy chemistry (e.g. adjusting Ni-Ti ratio or adding ternary alloying materials) and heat treatment [24]. This research uses Dynalloy Flexinol® wire with a stress-free austenite finish temperature $A_f \approx 90^\circ\text{C}$. The martensite finish temperature is approximately $M_f \approx 55^\circ\text{C}$.

3.2 CONTRACTILE SMA KNITTED ACTUATOR ARCHITECTURES

Contractile SMA knitted actuators are functional fabrics that accomplish large three-dimensional and distributed actuation deformations while exerting significant forces in response to thermo-mechanical loading. They are composed of a single strand of SMA wire, which is arranged into a network of interlacing knitted loops forming the wales (columns) and courses (rows) of the architecture.

SMA knitted actuators are hierarchical architectures [21] with design parameters on the respective hierarchical levels. The lowest level of hierarchy is the knitted loop, which is the fundamental element of knitted architectures. The knit loop and the purl loop are the geometrically indistinguishable unit cells, which only differ in their interlaced direction, specifically whether they are looped over or looped under the previous loop.

The next level of hierarchy is the knit pattern, which informs the assembly of knit and purl loops within the knitted architecture. The simplest knit pattern is the stockinette pattern, which uniquely consists of knit loops (Figure 5). The garter knit pattern is manufactured from alternating courses of knit and purl loops.

3.3 SMA KNITTED ACTUATOR OPERATION & PERFORMANCE

During the manufacturing process of contractile SMA knitted actuators, the originally straight SMA wire is bent into a network of interlacing loops. The imposition of bending

deformations on the originally straight wire functions as a potential energy storage, which can be transformed into kinetic energy through heating of the SMA knitted actuator above its austenite finish temperature. The partial recovery of these inelastic bending deformations in the knitted loop results in a macroscopic contraction of the complete knit pattern. For both architectures, stockinette and garter knit patterns, the recovery of this bending deformation leads to a straightening of the loops and produces planar uniaxial contractions in the course-wise direction (y-direction) (Figure 6). While both the garter and stockinette knit patterns share this effect, the asymmetry of the stockinette architecture can lead to bending around the x-axis under low mechanical loads, which results in increased actuation contractions.

The contractile SMA knitted actuators of this study are manufactured with Dynalloy Flexinol® wire ($A_f \approx 90^\circ\text{C}$, $M_f \approx 55^\circ\text{C}$). The contractile SMA knitted architecture is not stress-free due to the imposed bending deformations; therefore, the austenite finish temperature (A_f) can not be used as an indicator of the completed phase transformation. The magnitude and distribution of stresses throughout knitted architectures is complex and dependent on geometry and applied loads. Consequently, a higher temperature ($T_{op} = 120^\circ\text{C}$) than the stress-free austenite finish temperature is chosen to ensure larger austenite volume fractions in the partially-austenitic state, in which contracted SMA knitted actuators are compared. Alternatively, the lower operating temperature under which the knitted actuator is fully-martensitic can be exactly defined because the imposed stresses and strains strictly raise the martensite finish temperature. Consequently, fully-martensitic material is assumed for temperatures below the stress-free martensite finish temperature $M_f \approx 55^\circ\text{C}$.

The thermo-mechanical actuation performance of contractile SMA knitted actuators is most generally expressed with the characteristic temperature-dependent force-knit length profile. These profiles are obtained experimentally in uniaxial tension experiments conducted at $T = 20^\circ\text{C}$, for which the contractile SMA knitted actuator is fully-martensitic, as well as $T = 120^\circ\text{C}$, for which the knit is partially-austenitic (Figure 7). The fully-martensitic curve (blue) follows the established strain-hardening behavior of knitted architectures. Under low applied forces, the knitted architecture undergoes large changes in knit length utilizing the architectural mechanisms of relative loop sliding and loop bending deformation. However, under higher applied forces, the architectural deformation mechanisms are exhausted and additional deformations of the architecture require more energy. The partially-austenitic curve (red) does not follow the characteristic knit behavior. Under low applied loads, the stiffness of the architecture is relatively high, which can be attributed to an interlocking mechanism from straightening of the knitted loops, which creates less favorable frictional conditions and increases the architectural stiffness component. At high loads, the partially-austenitic curve approaches the behavior of the fully-martensitic curve due to the increasing volume fraction of martensite in the knitted actuator from stress-induced phase transformations. Between the two high-stiffness regimes is a transition regime with a relatively low stiffness at which the maximum %-actuation contraction occurs.

The shape and magnitudes of the force-knit length profiles are dependent on the contractile SMA knit geometric properties. The wire diameter and the knit index have been established as the smallest set of geometric parameters for the description of the garter contractile SMA

knitted actuator geometry and performance [10]. The knit index is defined as the fraction between the loop enclosed area (A_l) and the squared wire diameter (d) (Figure 8). The wire diameter of garter contractile SMA knitted actuators predicts the achievable actuation forces while the knit index predicts the fully-martensitic and partially-austenitic knit lengths and consequently the %-actuation contractions (Figure 8) [10]. The performance study of stockinette contractile SMA knitted actuators is in early stages and the exact geometric parameters that dictate the %-actuation contraction are not yet understood. Planar contraction and out-of-plane bending due to the architectural asymmetry contribute to the %-actuation contraction to an unknown degree depending on the geometric parameters of the stockinette contractile SMA knitted actuator and the applied forces.

4 SELF-FITTING SMA KNITTED GARMENT DESIGN

The design of a SMA knitted garment merges anthropometric, functional apparel, and active materials and structures research. The following sections describe the methods used to define the performance requirements and design the ideal contractile garment using SMA knitted fabrics.

4.1 ANTHROPOMETRIC ANALYSIS

The first step to design a self-fitting garment is to map the body-garment relationship. Prior research has shown that contractile SMA knitted actuators exhibit tunable functional performance through the systematic modification of geometric design parameters, specifically wire diameter and knit index [10]. Before we determined suitable knit geometries to achieve self-fit, the body-garment relationship was mapped. We began by gathering dimensional data from one male participant. Marks were placed on the participant's right leg from the ankle to the mid thigh in 2 cm increments. At each incremental mark, a circumferential measurement was taken with a standard apparel measuring tape. A subset of these lower-body measurements is displayed in Figure 9.

Once circumferential measurements had been gathered, we sought to define the performance requirements of the self-fitting garment. For an inextensible garment, the minimum garment dimension required at the base of a pant leg to enable don/doff (i.e. traverse the foot) is the calf dimension plus 2.5 cm of positive ease [25]. This recommended added garment dimension means that the garment circumference around the ankle should be equal to the garment dimension around the calf. Additionally, the garment dimension around the knee must be equal to the garment dimensions around the calf to enable the garment to traverse the calf. We modified the garment pattern slightly by adding a 7 cm taper from the knee to the ankle, a common, slimming pattern alteration. Figure 10 displays the required leg sleeve outlined around the participant's leg.

The required functional performance of the self-fitting garment is consequently defined as the percentual difference between the garment dimensions and the body dimensions. Figure 10 displays the required %-actuation contraction as defined by the garment-body interface. As shown in Figure 11, the garment begins in an oversized, compliant state (Fig.11 ①) with key dimensions displayed in Figure 10. When donned, force is applied to the garment as it is

pulled over the body (Fig.11 ②). Martensite relaxation occurs when the wearer releases the garment, now surrounding the body (Fig.11 ③). When actuated through body heat or other means, the garment contracts until it hits the reduced dimensions of the body, at which point interfacial pressure builds according to SMA knit's specific austenite curve. (Fig.11 ④). The primary challenge in the development of the proposed garment is to design a functionally gradient system that does not exert significant pressure on part of the leg and/or remain oversized in others.

4.2 GARMENT DESIGN CRITERIA

The design of a contractile SMA knitted garment, tuned to the dimensional requirements of the body, was accomplished through a clear set of required/exclusionary criteria. Figure 12 lays out the detailed design process in a flowchart with the three main criteria, performance, comfort, and manufacturability, which will be discussed among the secondary design criteria weight, ridge distance, and cost in the following sections. The design process is presented with the example of the self-fitting leg garment for the participant's anthropometry, however the language is kept intentionally general as the design process can be applied for any participant and body region.

4.2.1 Performance—The required %-actuation contraction ($\zeta_{n,req}$) at each of the 27 circumferential measurements was calculated by determining the percentual difference

$$\zeta_{n,req} = \frac{c_{n,garment} - c_{n,body}}{c_{n,garment}} \quad (1)$$

between the body's circumferences ($c_{n,body}$) and the circumferences of the pre-determined don-able/doff-able garment ($C_{n,garment}$), as shown in Figure 10 .

Each of the 27 circumferential measurements was matched with multiple SMA knits with comparable %-actuation contraction [10]. While contractile SMA knitted actuators with slightly higher nominal %-actuation contraction (+5%) are acceptable as they are not predicted to exceed the pressure limits (see section 4.2.2), fabrics with slightly lower %-actuation contraction (−1%) were immediately excluded from the selection because they do not accomplish fit.

4.2.2 Comfort—A successful self-fitting garment achieves fit without generating substantial pressure on the wearer's body, an objective that clearly distinguishes this research from medical applications that exert therapeutic pressures (18 mmHg or 2400 Pa) [20, 26]; however, pressures that are not substantial (i.e. pressures below the pressures exerted by socks, 1333 Pa) were deemed appropriate for this design. The pressure exerted by the self-fitting garment is calculated for each n -th circumferential measurement assuming rigid bodies. The hoop stress (σ_θ)

$$\sigma_\theta = \frac{F}{tw} \quad (2)$$

and the circumferential pressure (p)

$$p = \frac{\sigma_{\theta} t}{r} \quad (3)$$

are expressed through the fabric thickness (t), the limb radius (r), the fabric width (w), and the tensile force (F). Substituting Equation 2 into Equation 3 results in

$$p = \frac{F / w}{r} \quad (4)$$

an expression that relates the circumferential pressure (p) and the tensile force (F). Using the defined critical pressure ($p_{crit} = 1333$ Pa), the width of the circumferential measurement ($w = 0.02$ m), and rearranging Equation 4

$$F_{crit} = P_{crit} w r = (1333 \text{ Pa})(0.02 \text{ m})r \quad (5)$$

provides the critical force (F_{crit}), dependent on limb radius (r).

Implementation of Equation 5 is presented in Figure 13. While the original force-length profiles gathered from characterization by [10] presented data for 15 course by 15 wales knits, this data is scaled up for garment design, which will be discussed in Section 4.3. The critical force (Equation 5) at which the exerted pressure reaches 1333 Pa at the particular region's radius is marked by the horizontal line. Forces above F_{crit} enter the realm of medical pressure garments. Consequently, any knit whose $c_{n,body}$ and austenite curve intersect occurred above the F_{crit} line was eliminated as a possibility for the n -th circumferential measurement.

4.2.3 Manufacturability—We considered each circumferential measurement and paired contractile SMA knitted actuators in terms of adjacent pairings with the goal of building a unified garment structure. We observed that certain knits were unsuitable neighbors due to extreme differences in wire diameter that could threaten the structural integrity of the manufactured garment. Consequently, we selectively excluded any knits whose wire diameter was greater than 0.1 mm its adjacent wire diameter.

4.2.4 Additional Design Criteria—The previous design metrics thoroughly cover the known design space; however, if there were additional options remaining, supplementary criteria, specifically, comfort, weight, and cost, would be used. Figure 14 presents additional design criteria in terms of changing SMA knitted geometry. Specifically, we consider the impacts of loop size on touch comfort to mitigate sensations of point pressure [27]. With this data, knits with large knit indexes and large wire diameters at regions with heightened tactile acuity (e.g. mid-shin, front mid-thigh) can be mitigated. While further development is required to improve the wearer experience, we further consider comfort by prioritizing SMA knits with lighter weights. Finally, if there are comparable fabrics that could be used for the same region, the lowest priced fabric architecture should be chosen.

4.3 GARMENT MANUFACTURING

Once a suitable contractile SMA knitted actuator fabric had been chosen for each circumference, we began the manufacturing process. Traditionally, knitted patterns are generated by knitting a sample swatch with the chosen yarn and loop size. The number of wales and courses within a $2.5\text{ cm} \times 2.5\text{ cm}$ square are counted and these dimensions are scaled to achieve a knit pattern with desired dimensions. Once knit according to the pattern specifications, traditional yarn knit panels are washed, blocked, and steamed to relax the yarns into their new form. Finally, each garment panel is joined through a crochet, graft, or mattress stitch. Because our contractile SMA knitted actuator fabrics oscillate between different course-wise lengths with a change in temperature, we modified this process to fit our dynamic design. The following sections describe our design process and the methods that deviate from traditional knit manufacturing practices.

4.3.1 Course Mapping—We began the garment design process by scaling the 15 course by 15 wale contractile SMA knitted actuator data gathered from previous force-length characterization [10] to calculate knitted course requirements for each unique body circumference and SMA knit combination. Each of the 27 results are depicted in Appendix A. The plots include the austenite and martensite force-length curves scaled up to the body circumference measurement. Both the circumferential measurements ($c_{n,body}$) and the force at which garment pressure reaches 1333 Pa (F_{crit}) are included in the plots.

The number of knitted courses is determined through this scaling process and was adjusted slightly to ensure that the intersection between the body circumference and the austenite curves did not surpass F_{crit} . Additionally, we made adjustments if the body circumference line was to the right of the base of the martensite curve. In application, this means that the garment would begin compliant, but would already fit, or conform around the body region in the martensite state. In a commercial/consumer setting, this adjustment would not be necessary; however, for the purposes of a proof-of-concept prototype, we aim for the self-fitting capability to be visible. Because there will be some degree of martensite relaxation, as depicted in point 2 of Figure 11, we adjusted the austenitic loop number until the body circumference reached the minimum martensite knit length or F_{crit} , depending on which point was reached first.

4.3.2 Knit Pattern Generation—Once the number of courses had been determined for each of the 27 circumferential measurements of the body, the knit patterns, which provide detailed blueprints for knitted garment construction, were generated. Typically, circular garments such as socks, pants, or sleeves can be knit in the round, a technique which eliminates the need for joining seams. Circular knitting is not an option for self-fitting garments because the loops must be oriented in the circumferential direction to achieve the desired actuation contraction. Consequently, we designed our self-fitting garment as multiple flat knitted panels, each with a unique knit pattern, with joining seams.

Figure 15 depicts the full garment pattern with each of the 27 circumferential measurements indicated by a dotted line. Circumferential measurements that were paired with the same contractile SMA knit actuator fabric as their neighbor were grouped together to simplify the

knit pattern. These groupings formed discrete regions depicted in Figure 15. Once the discrete regions had been established, a shape was drawn around the edges of the regions to define the perimeter of the knit panel, indicated by a bold outline.

The 11 knit panels defined in Figure 15 are described further in Appendix B, which presents detailed knit patterns. At this point, the number of wales required to fill out each of the discrete regions was determined by evaluating contractile SMA knitted actuator fabric samples while fully martensitic and simply counting the number of wales within a 2 cm length (i.e. the minimum knitted panel width) and scaling to the required panel width. Because the perimeters of the knit panels are not always straight (for example, some are curved or diagonal), we employed a knitting technique call shaping, which involves selectively adding or dropping latch needles along the needle bed to respectively increase or decrease the width of the knit panel. In addition to filling in the required courses and wales to satisfy the functional requirements of the 11 panels, careful shaping was included in the knit patterns to smooth transitions and improve garment shape.

4.3.3 Knitting—The 11 knit panels were knit on a Taitexma TH-860 knitting machine with SMA wire (Dynalloy Flexinol®, $A_f = 90\text{ }^{\circ}\text{C}$) according to the pattern specification in Appendix B. In order to knit panels with edge shaping as one piece, loops would need to be added on one end of the knit panel and subtracted at the other end. Through experimentation, we discovered that the process of subtracting, or doubling over loops results in fabric curling upon actuation. In contrast, the process of adding, or spreading out loops results in further contraction upon actuation. Consequently, we sought to knit all edge conditions the same way and restrict our manufacturing process to include added loops only. To accomplish this design restriction, we split certain knit patterns in half and joined them vertically at the front and the back, while knit patterns that do not require edge shaping were knit in one piece and joined in the back only.

4.3.4 Thermal Blocking—As with fiber yarn knitting, contractile SMA knitted actuator fabrics require a post-knit step that allows the SMA monofilament to settle into its new architecture. Fiber yarn knits are generally washed, stretched, and pinned into their intended shape and exposed to steam, a process called blocking. The combination of applied force, heat, and water coaxes the yarn to relax into a new shape. Similarly, contractile SMA knitted actuator fabrics require thermal blocking, specifically a small applied load (50 g) and exposure to several thermal cycles ($20\text{ }^{\circ}\text{C} \rightarrow 120\text{ }^{\circ}\text{C}$), to settle into their intended length and width dimensions. Consequently, each knit panel was loaded with 50 grams, scaled according to the number of wales in the panel, and exposed to 5 cycles of thermal transition.

4.3.5 Knit Garment Assembly—Once the knit panels had been fabricated and thermally blocked, the panels were joined with a common crochet joining stitch to achieve the original garment design depicted in Figure 15. The final prototype, in a compliant, oversized state, is shown in Figure 16.

5 EXPERIMENTAL VALIDATION

The self-fitting garment was tested for its ability to contract around a custom-built test stand using three dimensional marker tracking. The prototype design is deemed successful if self-fitting is observed for the entire garment (i.e. the garment dimensions approximate the dimensions of the participant in the actuated state) and don/doff is feasible with the dimensions of the foot.

5.1 Three-Dimensional Marker Tracking

Three-dimensional marker tracking is a non-contact image acquisition and processing method to compute the time-history of motions and deformations using discrete points on solid structures. The marker tracking algorithm correlates the position of discrete bow-tie shaped markers in a reference image with their position in images after the solid structure has undergone deformations. This optical technology excels with its measurement speed, robustness and accuracy, and enables applications which would be unfeasible with conventional strain gauges [28]. A Correlated Solutions VIC-3D digital image correlation system with three dimensional marker tracking capabilities was used for the assessment of the garment contraction in this research. The images were acquired with two 5.0MP CMOS cameras (2448×2048) in a stereo setup using 1.4/17 mm lenses that provide the depth of field to focus on the markers despite the non-planar geometry of the leg and the large out-of-plane motion of the self-fitting garment.

5.2 EXPERIMENTAL SETUP

As the austenite finish temperature of the Dynalloy Flexinol® wire ($A_f \approx 90^\circ\text{C}$) is a higher temperature than humans can safely endure, a custom test stand was built for the experimental validation of the design. A molded replica of the participant's leg was manufactured from Densite® K-5 plaster. The leg replica was mounted to a stand with the foot pointing upwards to allow easy donning/doffing of the active garment (Figure 17).

Bow tie markers were equally distributed through all knit panels in a 3×13 pattern on the front and side of the self-fitting garment. Three marker along a circumferential segment form a circumferential marker triplet, between which displacements are measured in the experiment. Each marker was sewn to a single contact point on the vertex of a knitted loop, which prevents the markers from affecting the garment's actuation performance. After donning, the self-fitting garment was heated into its partially-austenitic, fitted state using conventional heat guns with a rated temperature above the stress-free austenite finish temperature of the Dynalloy Flexinol® wire. The three-dimensional motion of the bow tie markers was tracked throughout the experiment using the stereo camera setup. The cameras were arranged at an angle ($\alpha \approx 25^\circ$) normal of the leg circumference to increase the depth resolution of the marker tracking algorithm.

5.3 RESULTS

Due to the low stiffness of the oversized garment, a large amount of different geometric equilibrium states exist after donning the garment on the test stand. This variability of initial

geometric conditions causes large differences in measured displacements between the relaxed garment and the self-fitted, actuated garment. Statistical analysis was conducted to address the variability of initial geometric conditions.

Five experiments consisting of donning, actuating and doffing were conducted for each the front view and the side view of the leg replica. Both views were analyzed to ensure that the garment self-fit to the entire leg. In each experiment, the garment was donned in its fully-martensitic state at room temperature. After donning, the garment relaxed into an equilibrium state on the leg replica, which represented the initial condition and reference configuration of the experiment. The garment was subsequently heated to a temperature that exceeded the stress-free austenite finish temperature of the Dynalloy Flexinol® wire, which resulted in contraction to the fitted state. Throughout the process of self-fitting, the stereo camera setup captured the motion of the markers, which were fixed to the knitted loops of the garment.

Three-dimensional surface point coordinates of the bare leg replica, the oversized garment, and the self-fitted garment were measured using this technique. One objective of the experimental validation is to assess the quality of the fit post self-fitting, which is defined as the dimensional difference between the leg replica and the contracted garment. A comparison between the measured garment and leg replica dimensions is achieved through the construction of three dimensional surfaces from the three dimensional marker information (x, y, z) using Delauney triangulation and triangular surface plotting in Matlab. Figure 18a shows the overlaid surfaces of the leg replica, the fitted garment, and the oversized garment in the front view. The three-dimensional representation shows the qualitative difference between the oversized and contracted leg, however, quantitative measurements are difficult to extract from this view. Two-dimensional slices (Figure 18b) were cut out of the three-dimensional representation to assess the quality of the contracted garment fit. Comparison between the leg replica and fitted garment profiles in Figure 18b shows that accurate fitting is accomplished by the designed self-fitting garment with an average deviation of approximately 1.5 mm. This deviation can be attributed to the garment thickness, which ranges from 0.3 mm and 1.7 mm, as well as the marker uncertainty from the unconstrained rotational degrees of freedom of the single point attachment to the garment.

Another objective of the experimental validation was the comparison of the designed %-actuation contractions of the joined knit patterns with the measured %-actuation contractions on the leg replica. These measurements were conducted for each circumferential marker triplet, which are aligned in the actuation direction (y-direction). The Euclidean distances (E) between the center marker (x_c, y_c, z_c) and the outer markers $(x_{1,2}, y_{1,2}, z_{1,2})$ in each circumferential marker triplet were calculated

$$E = \sqrt{(x_1 - x_c)^2 + (y_1 - y_c)^2 + (z_1 - z_c)^2} + \sqrt{(x_2 - x_c)^2 + (y_2 - y_c)^2 + (z_2 - z_c)^2} \quad (6)$$

for the fully-martensitic, oversized garment after donning (E_{over}) and the partially-austenitic, self-fitted garment (E_{fitted}) after heating. The contractile ability of the self-fitting garment was validated by comparing the oversized and fitted garment Euclidean distances between the bow tie markers using the engineering strain definition

$$\varepsilon_m = \frac{E_{m,over} - E_{m,fitted}}{E_{m,over}} \quad (7)$$

for the m circumferential marker triplets. Figure 19 presents the results of the circumferential strain measurements in a) the front view and b) the side view. The average measurement of the five experiments in each view is displayed in Figure 19, the error bars show the variability between the experiments. Upon comparison with the designed %-actuation contraction requirements (Figure 20) it becomes apparent, that the measured actuation contractions have not fully met the design requirements. This mismatch can be attributed to the way that the self-fitting garment falls into an equilibrium state post donning, which is not perfectly circumferential as assumed in the design process, but can form folds and inconsistencies in response to variable topology. Therefore, the measured martensite dimension is smaller than the designed martensite dimension, and consequently the measured %-actuation contraction as well. Additionally, the stockinette knit segment (See Figure 15, segments 8 & 9) is fitted in its martensite state, which suggests that the number of courses was designed too conservatively and additional courses are required for self-fitting.

6 CONCLUSIONS

This paper presents the design process, manufacturing and experimental validation of an active-contracting, variable-stiffness garment for the lower extremities using contractile SMA knitted actuators. Anthropometric data was collected from a single male participant to provide the basis for this proof-of-concept prototype design. The participant's leg was measured circumferentially in n increments of 2 cm widths between the ankle and the thigh. Using standard garment design methodologies, the required dimensional ease to enable don/doff of a standard, non-stretch pant was calculated at each circumferential measurement. The dimensional difference between garment and body provided the required %-actuation contractions for the self-fitting garment. Contractile SMA knitted actuators that accomplish the actuation requirements were selected for each defined circumferential measurement. The complete design requirements are in descending order of importance: performance, comfort, and manufacturability. The active-contracting variable-stiffness garment was manufactured on a Taitexma-series knitting machine in separate knitted panels that met the design requirements of the individual segment and subsequently joined with a standard crochet stitch. The presented results validate the proposed design of a self-fitting garment using contractile SMA knitted actuators. Through optical measurement of the fabric surface deformations (3D Marker Tracking), complete self-fitting (i.e. the convergence of the garment dimensions to the dimensions of the leg replica) could be shown.

For the first time, a fully-functional, self-fitting, and self-stiffening garment was designed, manufactured, and experimentally validated. Future implementations of this design will

utilize SMA material that achieves self-fitting upon heating to the participant's skin temperature ($T_{skin} \approx 32$ °C) resulting in a self-powered, self-fitting garment. Through the design of a functionally gradient, self-fitting garment, this research addresses the challenges of achieving individual and population fit by establishing new garment design methodologies with active materials.

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Appendix

APPENDIX A: Dimensional Performance Plots Per Garment Region

Plots numbered 1-27 correspond to circumferential dimensions gathered from the participant's right leg in 2 cm increments.

APPENDIX B: Garment Pattern

Knit patterns numbered 1-11 correspond to the garment pattern presented in Figure 15.

① knit 2 pieces

Garter | $d = 0.203 \text{ mm}$ | $ki = 52 \text{ mm/mm}$

② double pattern

Garter | $d = 0.205 \text{ mm}$ | $ki = 63 \text{ mm/mm}$

③ double pattern

Garter | $d = 0.254 \text{ mm}$ | $ki = 71 \text{ mm/mm}$

④ double pattern

Garter | $d = 0.203 \text{ mm}$ | $ki = 98 \text{ mm/mm}$

Knit Stitch

Purl Stitch

Garter:

Knit and Purl Stitches

Stockinette:

Knit Stitches

⑤ double pattern

Garter | $d = 0.254 \text{ mm}$ | $ki = 71 \text{ mm/mm}$

⑥ double pattern

Garter | $d = 0.305 \text{ mm}$ | $ki = 63 \text{ mm/mm}$

⑦ knit 1 piece

Garter | $d = 0.203 \text{ mm}$ | $ki = 52 \text{ mm/mm}$

⑦ knit 1 piece

Garter | $d = 0.203 \text{ mm}$ | $ki = 52 \text{ mm/mm}$

Knit Stitch

Purl Stitch

 Garter:
Knit and Purl Stitches

 Stockinette:
Knit Stitches

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Figure 1: Inter- and Intra-Subject Anthropometric Variability:
Cross-sections taken from randomly selected male subjects from the Civilian American & European Surface Anthropometry Resource (CAESAR [11]).

Figure 2: Sizing for Apparel Market:

Mass produced garments are designed to fit the public by forcing a correlation between two or more body dimensions and blocking out sizes categories (e.g. small (S), medium-narrow (M-n), medium-wide (M-w), large (L)), as depicted by the solid black boxes. This method results in major portions of the population un-fit, as depicted by the red points outside of the size chosen categories. [13]

Figure 3: Garment Don/Off Design Logistics:

(A) Inextensible garments must be designed with positive ease to traverse the foot, or (B) inextensible garment must be designed with closures (e.g. zipper) that can open for don/doff and close to achieve fit. (c) Fitted garments can also be made with extensible fabrics that strain to traverse the foot. These garments are designed with negative ease to ensure fit.

Figure 4: Proposed Self-Fitting Garment:

(1) The proposed garment is compliant and oversized before don. (2) During the donning process, the compliant garment is stretched out further as it is pulled over the limbs. (3) Once on the body and free of external forces, the garment slightly relaxes around its new form (4) The garment then warms to skin temperature, which causes contraction and stiffening. To doff, the garment would either need to be cooled or designed with release mechanisms.

Figure 5: Contractile Knit Patterns:

The stockinette knit pattern consists uniquely of knit loops whereas the garter knit pattern consists of alternating courses of knit (gold) and purl (maroon) loops. Both patterns are shown in their front view (xy) and their side view (yz).

Figure 6: Contractile SMA Knit Actuation Mechanisms:

Stockinette and garter SMA knitted actuators provide macroscopically uniaxial actuation contractions. While garter contractile SMA knitted actuators always produce planar actuation contractions, stockinette contractile SMA knitted actuators produces macroscopic bending deformations around the x-axis for specific geometric parameters and applied loads.

Figure 7: Contractile SMA Knitted Actuator Performance:

The characteristic force-knit length profiles for a fully-martensitic (blue) and partially-austenitic (red) SMA knitted actuator. The difference between these profiles is the %-actuation contraction (ζ) with the distinct point of maximum %-actuation contraction ($\hat{\zeta}$).

Figure 8: Contractile SMA Knitted Actuator Performance:

The knit index (i_k), defined as the fraction of loop enclosed area (A_l) and the squared wire diameter (d), linearly predicts the maximum %-actuation contraction of garter contractile SMA knitted actuators. Stockinette contractile SMA knitted actuators show actuation contractions that can be attributed to out-of-plane bending and to planar contraction.

Figure 9: Anthropometric Analysis for a Lower Body Garment:

(left) Circumferential measurements were taken in 2 cm increments along the length of the participant's right leg. Abbreviated dimensions are displayed here. (right) The circumferential measurements were increased to enable garment don/doff according to [25] and the percent difference between the garment and body measurements were calculated.

Figure 10: Fit and Performance Requirements for Self-Fitting Garment:
 Garment ease is greatest around the ankle and knee due to donning logistics and, consequently, require greater contraction to achieve fit.

Figure 11: Self-fitting Garment Operation:

The fully-martensitic garment is compliant and oversized (1). Upon donning, small forces are exerted on the garment, which cause further garment dimensional expansion (2). Upon release, the garment contracts into its martensite relaxed state and recovers some of the extension from the donning process (3). Heating (body or external source) causes the garment circumference and the leg circumference to equate (4). Additional contractile ability of the garment results in a generation of forces and pressure on the leg, which are to be minimized in the design.

Figure 12: Design Flowchart:

The contractile SMA knitted actuator design for N circumferences is based on three design constraints: (1) Performance - provide required actuation contraction ($\zeta_{n,req}$), (2) Comfort - remain below acceptable surface pressure $p_{max} = 1333\text{Pa}$, and (3) Manufacturability - neighboring wire diameters $d_n, d_{n\pm1}$ within limitations for difference in magnitude.

Figure 13: Maximum Pressure Calculations:

Pressure on the body is determined by the relationship between force per fabric width and body radius (Equation 4). Consequently, the critical force (F_{crit}) at which pressure reaches (1333 Pa) is determined by the dynamic garment-body interaction and is unique to each SMA knit + body region combination (Equation 5).

Figure 14: Additional Design Criteria:

The additional design criteria mass, cost, and ridge distance were used when multiple knit patterns met the stated requirements. The desirable lower/smaller values are displayed in green and the higher/larger values in red.

Figure 15: Garment Pattern:

Each body circumferential measurement, represented by a dotted line, is grouped with neighboring circumferences that require identical knit architectures. Eleven knit panels, outlined in black, make up the full garment design. See Appendix B for detailed patterns.

Figure 16: Active-Contracting, Variable-Stiffness SMA Knit Garment Prototype in an Unactuated State:

(left) Front view, full garment. (right) Side view, thigh closeup. The prototype garment was knit according to the specifications in Appendix B.

Figure 17: Experimental Validation Method:

The design of the active-contracting variable-stiffness fabric for self-fitting wearables is validating using 3D marker tracking by heating on a replica of the participant's leg. The markers are assembled in circumferential triplets (1, c (center), 2)

Figure 18: 3D Triangular Surface Plot & 2D Slice:

a) Triangular surfaces were defined from the marker coordinates to build three-dimensional surfaces of the leg replica, fitted garment, and oversized garment. b) Two-dimensional slices were extracted from these surfaces to evaluate the contracted garment fit quality. An average deviation between the fitted garment and the leg replica of less than 3 mm demonstrates the accurate self-fitting of the active-contracting garment.

Figure 19: Circumferential Contraction:

The average %-actuation contraction from five experiments is plotted in red for the a) front and b) side view for each circumferential marker triplet. The error bars show the measured variance, which can be attributed to different initial conditions after donning.

Figure 20: Actuation Contraction Requirements vs Experimental Findings:

The experimental findings (ζ_{exp}) conclude that our self-fitting garment achieves the required contraction (ζ_{req}) at the garment ends; however, the prototype undercontracts in the center of the garment.