Proceedings of the 2019 Design of Medical Devices Conference
DMD2019
April 15, 16-18, 2019, Minneapolis, MN, USA

DMD2019-3290

TOWARD TEXTILE-BASED HEATING DEVICES FOR THE DISTAL EXTREMITIES: EXPERIMENTAL CHARACTERIZATION OF SYSTEM DESIGN PARAMETERS

Ellen Dupler[1], Nika Gagliardi, Esther Foo, Simon Ozbek, Sophia Utset-Ward, Lucy Dunne
University of Minnesota
Minneapolis, Minnesota, USA

ABSTRACT

Supplemental heating systems for the distal extremities often require a tradeoff between wearability and thermal comfort. Textile-based thermal actuation helps manage this tradeoff by increasing comfort of on-body systems. However, textile-based thermal actuation also presents important limitations in the form of current requirements, control structures, and thermal flux afforded. Further, on-body active thermal control is affected by three intersecting thermal systems: the environment, the human body, and the active heating system. Here, we present lessons learned from iterative development of textile-based wearable systems (V1, V2) designed to heat the distal extremities. Experimental characterization of textile actuator power/temperature relationships and limits; actuator performance in cool ambient temperatures and in on-body conditions; and efficacy of closed-loop duty cycle control of actuated skin temperature are presented, and implications of these characteristics for garment system design are discussed.

Keywords: wearable technology; e-textiles; thermal systems; thermoregulation

INTRODUCTION

On-body thermal systems have a variety of potential applications. For instance, heating systems can be used for improving comfort in cold environments [1], reducing energy expenditure spent heating large spaces [1,2], and treating medical patients with certain thermoregulatory disorders [3]. The approximately 28 million individuals with Raynaud's disease (a vasospastic disorder that causes discomfort from excessive numbing and vasoconstriction in the peripheral digits in reaction to cool environments), and those with illnesses that have Raynaud's symptoms (Lupus, Buerger's disease, and Scleroderma, to name only a few), are particularly benefited by such on-body thermal systems.

Products offered to those with Raynaud's symptoms frequently consist of either: traditional passive insulation garments (gloves); one-time use chemical heat strips; or bulky rigid devices that are either hand-held or worn over the entire hand--both of which inhibit dexterity. Textile-based active heating integrated into garments (e.g. sleeve cuffs or similar) may offer a comfortable, wearable heat source for everyday use. However, effective design of such systems relies on characterization of implementation variables in actuator fabrication, power requirements, and feedback mechanisms. Here, we describe results from actuator development and two system implementation iterations with respect to temperature/power relationships and control mechanisms.

ACTUATOR CHARACTERIZATION

The actuators used in the device development described here operate on the resistive or Joule heating principle, wherein an electrical current running through a conductive element is used to generate heat. In all our studies, the conductor used is sewable Syscom Liberator 40® silver-coated Vectran™ multifilament thread (Kuraray Co. Ltd.). In prior work [4], actuator design variables including power/ resistance/ temperature relationships, effects of substrate materials, effects of trace spacing, and effects of covering layers were characterized. These results were used to select best-fit characteristics for the heated garment, described in the next section. Figures 1 and 2 present general characteristics of these actuators.

Beyond one Amp (1A) the resistance of the thermal actuator deviates from linear behavior (Fig.2). To reduce the effect of nonlinear heating behavior in the system and to avoid high-current risks for human subjects, the current was limited to 1A or less for all tests.

[1] Contact author: duple004@umn.edu

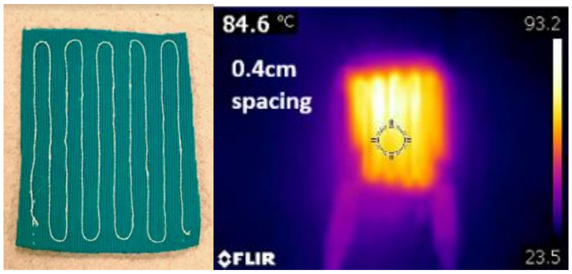

FIGURE 1: (LEFT) STITCHED ACTUATOR (RIGHT) THERMAL IMAGE OF STITCHED ACTUATOR

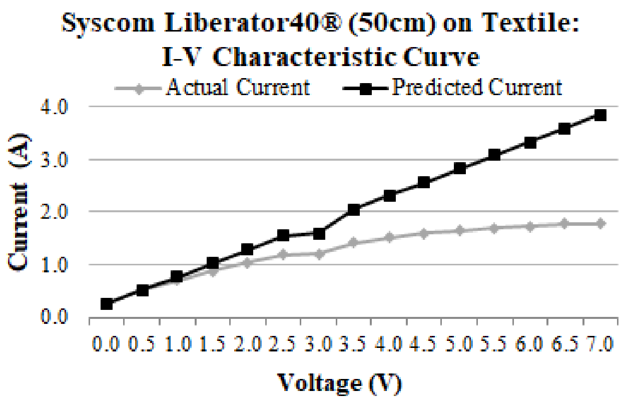

FIGURE 2: ACTUATOR IV-CHARACTERISTIC CURVE

To ensure that other materials in the system (such as textile substrate and non-conductive thread) could sustain the desired temperatures required by the thermal actuator, three actuator swatches (4.0 x 5.5cm^2 swatches with 50cm conductive thread) were tested to failure. Temperatures generated by the system onto the skin were desired to meet the range of typical room temperatures (20-40°C) below documented pain threshold [5].

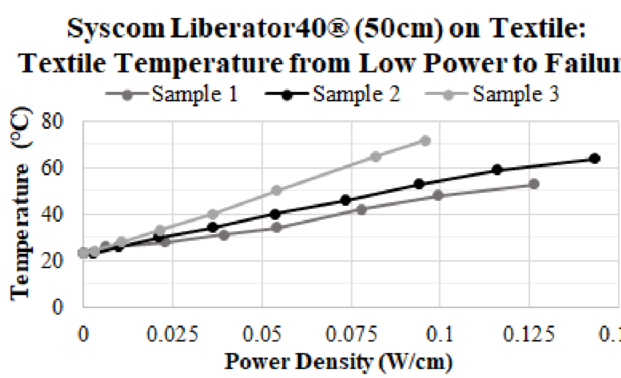

FIGURE 3: ACTUATOR TEMPERATURE RESPONSE

As seen in Figure 3, swatches failed between 0.096 and 0.14 W/cm, corresponding to a temperature range of 53-72°C +/-2°C. In this system, it was the non-conductive polyester thread used in the needle thread of the lockstitch that failed first, then the polyester-spandex blend textile, indicating that hotter temperatures could be achieved with different materials. However, this temperature range exceeds the estimated pain threshold (roughly 42°C) by 10 degrees or more, so these materials were deemed adequate for our application.

V1 FIXED-TEMPERATURE GARMENT DEVICE

1.1 Device Design

The actuator described in the previous section was implemented in a first-iteration wearable device. This device is described further in [6], and summarized here. The first-iteration device was designed to facilitate two heat-distribution conditions: wrist-only heating (dorsal and palmar wrist) and wrist-and-hand heating (wrist areas plus dorsal and palmar hand, not including the fingers).

The garment was designed as a sleeve cuff extending over the palm with a hole for the thumb in a 3-layer assembly: the heating element on the outside of the polyester-spandex knit base layer; an aluminized mylar film layer (Foil Mylar, Primacare) above to improve heat retention; and a textile cover layer on the outside (Fig.4) [4].

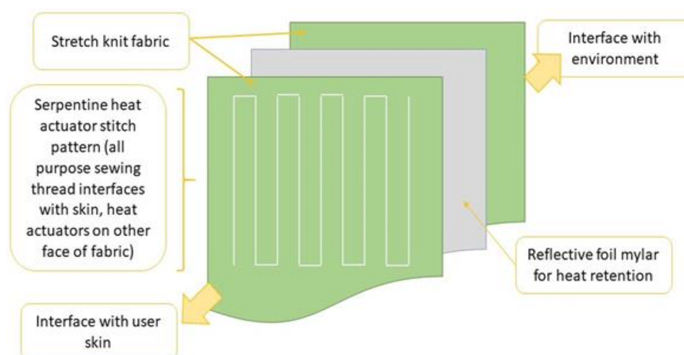

FIGURE 4: V1 GARMENT TEXTILE LAYUP [6]

Nine garments in two sizes (small and large) were fabricated in order to evaluate design variability between garments, allow redundancy in garments during user testing, and fit the anthropometrics of participants. Actuator patterns (conductive fiber configurations) were consistent lengths for both small and large garment sizes, and a similar length in the wrist zone and the hand zone. However, variation in the amount of conductive fiber used was introduced by the sewing process, resulting in variable resistance values ranging from 6.39Ω to 7.39Ω ($\bar{x}$=6.89Ω).

The system design of this garment involved no control circuitry (garments were powered directly from an external power supply via metal snap connectors). Therefore, to establish power settings for target temperatures the garment temperature/voltage relationships were characterized in ambient indoor temperatures prior to a cold-chamber human test. Three garment temperatures were characterized: 33°C, 37.5°C, and 40°C, ranging from just above room temperature to just below a documented pain threshold skin temperature [5]. Individualized power settings for each garment were empirically determined by incrementally adjusting the power settings and measuring the thermal output, to account for variation between garments. Each garment (3-material layer system) was placed on a work table and tested with two thermistors (NTC 10kΩ, 1% Disc, TDK

Corporation) applied to hand and wrist zones on the innermost garment layer, while power was supplied by a DC Power Supply (Dr. Meter HY3005F-3) for five minutes until temperature plateaued. The achieved temperature was recorded and compared against the desired three setpoints. If slightly under or above, the garment was allowed five minutes to cool and power was adjusted and retested until setpoints were met (Table 1).

TABLE 1: BENCH TESTED ACTUATOR POWER SETTINGS PRE-CHAMBER ($\bar{x}$=6.89 Ω)

Temperature	Power Requirements (W)	
Setpoint	**Range**	**Average**
33°C	0.7 - 1.2 W	0.9 W
37.5°C	1.1 - 1.6 W	1.3 W
40°C	1.3 - 1.9 W	1.6 W

For human testing, a fuse (1A current rating, Schurter Inc.) was implemented in the garment design to prevent overcurrent complications.

1.2 Test Methods and Results

A performance test with 6 participants (3 female/3 male, ages 21-30) was conducted in a controllable thermal chamber (12'6" by 7'6" and 7'0" tall) set at 18°C [6]. The testing was done during August, at the end of the summer season.

Garments were initially pre-warmed inside the cool chamber. During this process, it became apparent that the bench-tested power settings did not translate (in terms of temperatures produced) to the cooler environmental temperature. New power settings were determined using the previously described process on-site in the chamber and measured approximately 1-2W higher than bench tested conditions (Table 2).

TABLE 2: ADJUSTED GARMENT POWER SETTINGS FOR 18°C ENVIRONMENT ($\bar{x}$=6.89 Ω)

Temperature	Power Requirements (W)	
Setpoint	**Range**	**Average**
33°C	1.6 - 2.5 W	2.0 W
37.5°C	2.0 - 4.0 W	2.8 W
40°C	2.2 - 4.7 W	3.6 W

Each garment was prewarmed using the new characterization data and placed on the participants' right hand only. Power was fixed for each condition and was not varied during the testing period. Skin temperatures of the fingertip, axillary fold, and dorsal and palmar areas of the wrist and hand were measured with NTC thermistors placed upon the skin with medical tape for the duration of testing. Temperatures sensed with the NTC thermistors were recorded through a NI-USB 6001 data acquisition system. Methods discussed further in [6].

Results of this investigation showed considerable variability in the temperatures experienced by the participants, as well as a frequent inability to reach the desired heat setpoints (Figs. 5, 6). Notably, participants did not start with the same base temperature at the start of each test. The range of temperatures experienced as well as the highest temperature achieved for each participant/test condition is variable, even with increased power to the garment for higher setpoints. Across participants there was a range of 5-14°C between the lowest measured temperature to the highest for each condition (represented in Figures 5 and 6 by the length of the bar).

In the Wrist-Only 33°C, 37.5°C, and 40°C conditions, some participants followed a clearer progression of increased wrist temperatures with increasing setpoint (e.g. P3, P4) while others did not (e.g. P1, P6) (Fig.5).

In the Full Cuff (wrist/hand) conditions, participants' wrist skin temperatures experienced smaller fluctuations (1-9°C) compared to that of the hand (3-12°C) (Fig.6). The variability of skin temperatures seen in the wrist and hand (both within participant testing and between participant testing) dominate any potential trends from the increased power to the V1 garments for the three different setpoints.

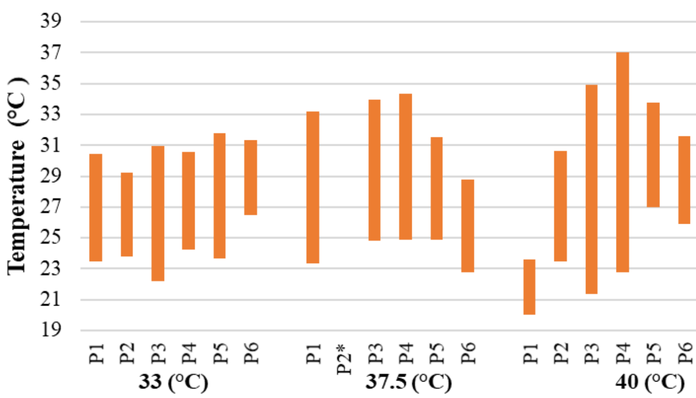

FIGURE 5: WRIST SKIN TEMP IN HEATED WRIST-ONLY CONDITIONS
*= data missing due to collection error

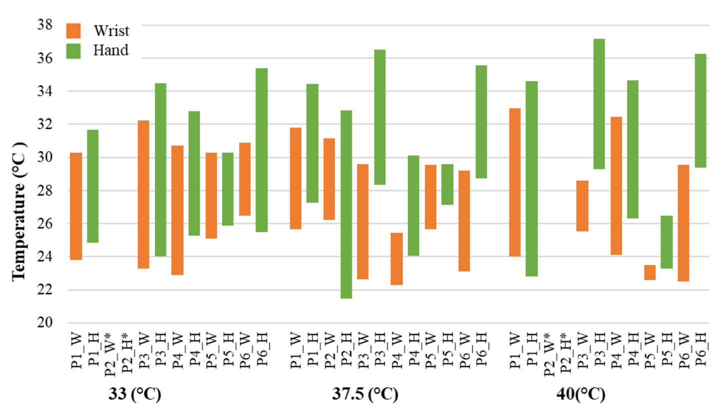

FIGURE 6 HAND & WRIST SKIN TEMP IN HEATED FULL CUFF CONDITIONS
*= data missing due to collection error

These results illustrated the additional environmental and physiological variables influencing device performance: ambient temperature and humidity, as well as the skin/core temperature and vascular physiology of each participant, prevented a current-controlled fixed garment temperature from maintaining a stable skin temperature across subjects. Based on these results, a second-generation device was developed.

V2 SELF-REGULATED GARMENT DEVICE

2.1 Device Design

The next iteration of the device was developed with modifications to both the garment and system in the first design. The 0.4cm spacing for the serpentine conductive traces was maintained, but the trace pattern was modified to better distribute the actuator traces within the surface area of each garment size. A fuse (1A) was again added to provide overcurrent protection.

In the V1 design, the added Mylar layer in the system was intended to improve radiant heat retention, but subsequent bench tests performed to test this hypothesis with the system did not show added efficiency. Further, the foil impeded material flexibility. This layer was therefore removed for this iteration. Additionally, a wristlet garment was made to compare against the original garment design as illustrated in Figure 7. Both garment designs were fabricated with an added zipper on the side to aid in donning and doffing. Actuator zones for both wrist and hand were included in the full cuff garment as before, whereas the wristlet garment had only a wrist zone.

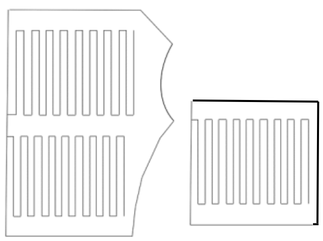

FIGURE 7: DESIGN ILLUSTRATION (LEFT) FULL CUFF GARMENT (RIGHT) WRISTLET GARMENT

The V2 garment design addressed the challenge of maintaining a consistent temperature experience for each participant by implementing integrated closed-loop skin temperature feedback using NTC thermistors placed immediately underneath each zone and microcontroller-based control system (Arduino Mega). The original thermistors were replaced with alternative NTC thermistors (10kΩ, 3% Disc, Vishay BC Components) due to their faster reading response time and planar form, which was found to be better for the application of measuring temperature of the skin. A ten-point moving average temperature was used to control activation of the actuator, at a 5 Hz sampling rate. To isolate the high-current thermal system from the low-power microcontroller circuit, garment actuators were controlled using transistor-driven relays (Fig.8).

The resistance of the thermal actuator in the wrist zone ranged from 6.3Ω to 6.5Ω ($\bar{x}$=6.4Ω) for the small size and 8.3Ω to 8.9Ω ($\bar{x}$=8.6Ω) for the large size. The resistance of the thermal actuator in the hand zone ranged from 7.3Ω to 9.1Ω ($\bar{x}$=8.5Ω) for the small size and 9.2Ω to 9.5Ω ($\bar{x}$=9.4Ω) for the large size.

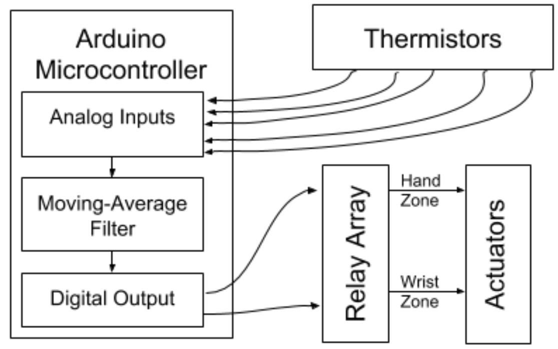

FIGURE 8: SCHEMATIC OF V2 SYSTEM DESIGN

2.2 Test Methods and Results

The testing protocol was similar to the first thermal chamber test [6] with some key differences. For the wrist-only zone heating conditions, the wristlet garment was used to leave the rest of the hand bare.

The same thermal chamber was set to 20°C and 6 participants were tested (3 female/3 male, ages 22-30). (Note: P1-6 for V1 testing are different participants from P1-6 in V2, except for 2 male participants. However, their participant ID is not the same for both studies.) The testing was done during April, at the end of winter season of colder temperatures. Heated garment setpoint temperatures of 33°C and 38°C for each zone were selected (38°C chosen instead of the 37.5°C and 40°C setpoints used in previous chamber testing).

While participants remained seated throughout the testing with arms placed ~90deg on a table, a preheated garment was applied to the right hand and thermistors were used to monitor temperatures. The order of temperature setpoint conditions were randomized, and the participant either started first with the full cuff garment or with the wristlet. Each participant wore both garments.

Because the self-regulated garment could control only duty cycle of the actuator, not current supplied to the actuator, a range of estimated power settings was used in order to enable the garment to reach setpoint temperature within the 5-minute test period without exceeding the 1A threshold. Settings were determined after bench testing with the V2 garment in ambient temperature (~23°C) and increasing power slightly for the cooler environmental chamber testing. (Table 3). Despite attempts to use the same actuator supply power for each participant, the initial skin temperature baseline influenced the supply power used to achieve setpoint temperature for a particular test condition. Therefore, power settings were not fixed as in the first phase testing but were calibrated to each user during testing.

Overall, participant baseline temperature had more influence on selected power settings than garment resistance. To note, one participant already had a skin temperature of 33°C, so the thermal actuator was not triggered to turn on for one test condition.

For each test condition, the temperature for each thermistor location and the power duty cycle was monitored; the results for one test condition, P6 Wrist 38°C is shown in Figure 9.

TABLE 3: GARMENT POWER SETTINGS USED DURING HUMAN SUBJECTS TESTING IN 20°C ENVIRONMENT

	Garment Size	Setpoint Temp	Range of Power	Average Power
Wrist Zone	S	33°C	3.0-4.8 W	3.8W
Small $\bar{x}$=6.4Ω)	L	33°C	0.0-3.7 W	2.4 W
Large	S	38°C	5.8-8.3 W	6.8 W
($\bar{x}$=8.6Ω)	L	38°C	5.0-7.8 W	6.3 W
Hand Zone	S	33°C	2.3-4.8 W	3.6 W
Small	L	33°C	2.0-2.9 W	2.4 W
($\bar{x}$=8.5Ω)	S	38°C	4.8-10.1 W	6.9 W
Large ($\bar{x}$=9.4Ω)	L	38°C	3.1-8.4 W	4.9 W

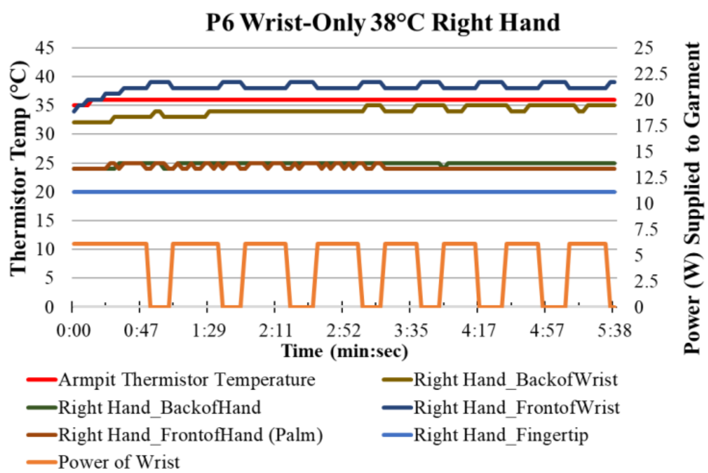

FIGURE 9: EXPERIENCED TEMPERATURE RESPONSE AND GARMENT POWER DUTY CYCLES FOR PARTICIPANT 6 WRIST GARMENT SET AT 38°C

The results of experienced temperatures for all participants and test conditions are shown in Figure 10 for the wristlet garment and Figure 11 for the full cuff garment.

In the Wrist 33°C Condition, measured temperatures reached setpoint with only P5 exhibiting a larger "overshooting" fluctuation in the positive direction (+3°C rather than +1°C) (Fig.10). The 38°C setpoint was successfully reached for all participants in the Wrist 38°C Condition, with limited overshooting (0-1° C).

For the Full Cuff Conditions (wrist/hand), the 33°C setpoint was reached for all participants in the hand and wrist zone, with the exception of two participants' hand zone (P3_H, P4_H) (Fig.11). Conversely, while the setpoint of 38°C was readily achieved in the wrist zone for all participants, only two participants were able to reach setpoint on the hand zone (P3_H, P5_H). For this condition, the current required for the hand zone approached 1A, limiting the input power needed to accommodate the slightly larger area and looser fitting portion of the garment.

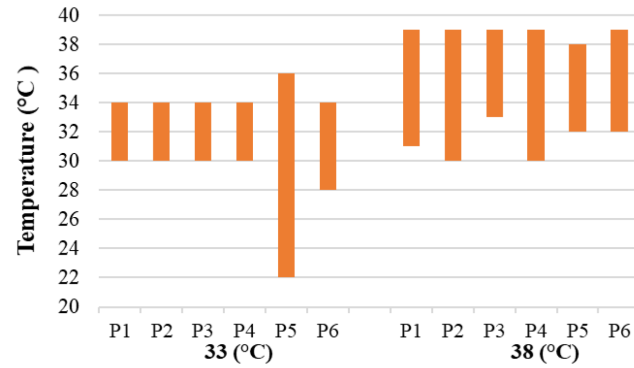

FIGURE 10: WRIST SKIN TEMP IN HEATED WRISTLET

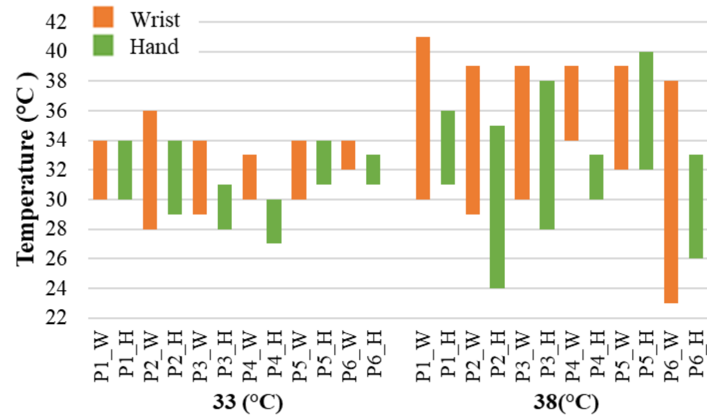

FIGURE 11: HAND & WRIST SKIN TEMP IN HEATED FULL CUFF

Overall, the variation of the V2 system is much improved over the V1 system, with experienced temperatures reaching the target setpoints. Regardless of how low participants' wrist temperatures initially were, both the full cuff and wrist garment zones were successful in warming the wrist to reach the setpoint within the 5min time and self-regulate to either 33°C or 38°C for all tested participants, and successful in warming the hand for the majority.

There are three main factors that the thermal actuating system must take in consideration to be fully successful. The first is the Joule heating capacity of the textile actuators and its relationship to surface area. Although our actuator failure tests showed the swatches were capable of exceeding human comfort temperature limits, the heating filaments localize the generated heat in close proximity to failure-prone materials (i.e. polyester). Even though the filament gets quite hot, the heat flux is relatively small due to the small diameter of the heating filaments. Further, the resistance of each heating zone approaches the 1A current restriction placed on each zone before adequate surface temperatures are reached, limiting the warming capability of larger zones (with larger heat-sinking capability) in the garment for higher setpoint temperatures.

The second factor is the variation in heat sinking capability of the human users' bodies. The self-regulating design senses a temperature has not been met but does not yet accommodate for the rate of temperature change due to being worn by a human hand cooler than the garment itself. This results in a varying system response as it adapts providing power to maintain the same temperature. These aspects affect the ability of the garments to establish and maintain higher skin temperatures.

In addition, in chamber trials subjective feedback from participants made a third factor clear: that body setpoint temperatures (comfort thresholds) mediated the experience of comfort near the thermoneutral zone. Some participants were too warm even in the coolest setting, and some were too cold even at temperatures that should near the pain threshold. Furthermore, as the garment is worn, the user's desired temperature setpoint may change and the system control must adjust to user preferences to be deemed as successful in meeting thermal comfort needs.

USER-CONTROLLABLE SELF-REGULATED GARMENT DESIGN

The test results for the V2 garment indicated that system developments were successful in reaching and maintaining a warming temperature setpoint of 33-38°C to the human wrist, but that currents higher than 1A may be needed for adequate thermal flux, and that there was strong variability in participants' thermal preferences as well as physiological responses. However, current control on the actuator side would present a more significant system design challenge. For these reasons, the V3 system design (Fig.12) is currently under development. The design will incorporate high temperature thread (replacing the polyester thread), additional electrical insulation to limit the risk of high-current hazards (to increase the amperage threshold for the actuators), and will integrate a user-controllable temperature setting to enable closed-loop control of garment thermal setpoint by the participant. The thermistor feedback control will still be used to maintain internal temperature through duty cycling. An additional potentiometer dial will allow users to control the desired setpoint of each thermal actuator, adjusting the control setpoint and power supplied to the thermal actuators accordingly.

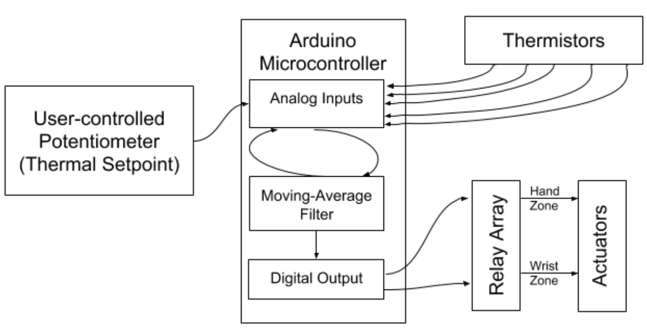

FIGURE 12: SCHEMATIC OF V3 SYSTEM DESIGN

CONCLUSIONS AND FUTURE WORK

The system design characteristics established through these iterative experimental investigations highlight the complexity of effective microclimate control on the human body. Investigations into actuator design illustrate limitations of soft thermal actuators (particularly in thermal density/localization when using fiber-type actuators, which is incompatible with the relatively low melt/burn points of common textile materials and current limitations for on-body applications). Yet, they demonstrate the feasibility of working within these limitations to meet the requirements for effective near-skin actuation.

Bench characterization of the V1 device performance was inadequate for the more complex thermal environment in which it was tested, indicating the need to account for both ambient and body thermal effects on system output.

The V2 device was capable of self-regulating to produce a consistent skin temperature. However, variability in requisite power supplied and desired thermal setpoints from the user perspective limits this approach from achieving sufficient microclimate control. The V3 device seeks to address this obstacle by increasing feasible supply currents and putting device control in the wearer's hands. In this way we hope to more effectively characterize the scope of temperature/comfort relationships in the near-body microclimate.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation under grant #1646543, and by the Minnesota Agricultural Experiment Station under project MIN-53-031.

We would also like to thank Katherine Yan for assisting in V3 potentiometer research and integration.

REFERENCES

[1] Newsham, G., "Clothing as a thermal comfort moderator and the effect on energy consumption," *Energy Build*., vol. 26, no. 3, pp. 283–291, 1997.

[2] Arens, E., Zhang, H., and Huizenga, C., "Partial- and whole-body thermal sensation and comfort, Part I: Uniform environmental conditions," *Cent. Built Environ.,* Nov. 2005.

[3] Charkoudian, N., "Skin Blood Flow in Adult Human Thermoregulation: How It Works, When It Does Not, and Why," *in Mayo Clinic Proc.*, 2003, pp. 603-612

[4] Foo, E., Gagliardi, N., Schleif, N., and Dunne, L., "Toward the Development of Customizable Textile-integrated Thermal Actuators," *in Proc. of the 2017 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2017 ACM International Symposium on Wearable Computers*, 2017, pp. 29–32.

[5] Defrin, R., Shachal-Shiffer, M., Hadgadg, M., and Peretz, C., "Quantitative somatosensory testing of warm and heat-pain thresholds: The effect of body region and testing method," *Clin. J. Pain*, vol. 22, no. 2, pp. 130– 136, 2006.

[6] Gagliardi, N., Foo, E., Dupler, E., Ozbek, S., and Dunne, L., "Design of a Stitched Textile-based Thermal Actuator Garment To Attenuate Peripheral Microclimate Experience, " *Proc. of the 2018 Design of Medical Devices Conference*, 2018.