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DESIGN OF A STITCHED TEXTILE-BASED THERMAL ACTUATOR GARMENT TO ATTENUATE PERIPHERAL MICROCLIMATE EXPERIENCE

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BACKGROUND

Temperature is an important influencer of homeostatic comfort for humans, and its influence extends beyond life-preservation functions into cognitive and emotional effects. To augment metabolic processes in cold climates, many on-body heating solutions are currently available in the commercial market, ranging from chemical heat packs to electrically heated accessories and clothing. These products typically prioritize heating the body core in extreme conditions. By contrast, the experience of thermal comfort in the band around homeostatic comfort temperatures is much more strongly driven by experience of temperature in the body's periphery: the hands, feet, and face [1]. Thermal sensitivity is highest in the distal extremities and has been established as the best correlate of overall perception of thermal comfort [2], [3]. In the medical context, this is especially significant in treating vasospastic disorders such as Raynaud's Syndrome, where a spastic vascular response in peripheral vessels results in an over-reaction to cold temperatures proximal to the thermoneutral zone [4].

Delivering heat to these areas is most commonly achieved through environmental systems (indoor heating), and is much more difficult to achieve with on-body systems due to the comfort challenges of wearing gloves/masks in non-extreme conditions. The hands, in particular, are very likely to be exposed to ambient conditions, and difficult to cover comfortably. Therefore, comfortable methods of effectively delivering heat to the hands are necessary.

This research focuses on mediating the earliest stages of indoor thermal discomfort by providing supplemental heat to attenuate thermal experience in colder ambient temperatures. Specifically, we seek to develop on-body actuation technologies that allow the design space to be more fully explored. Technologies like thermoelectric generators (TEGs) that typically take rigid, planar structures inherently limit the flexibility and geometry of on-body thermal actuation. Instead, we explore a textile-based technology for on-body heating, which enables fully customizable layouts within typical textile structures so that the effects of higher-resolution, spatially distributed temperature control can be investigated. Our stitched textile-based actuator is implemented in two distal heating conditions, wrist-only and wrist and hand, and the relative effects of these heating conditions on skin temperature over the hand surface are measured in a pilot investigation.

METHODS

Stitched Thermal Actuator

Any on-body heating device is inherently restricted by the adaptability of its actuator. While thermo-electric devices are a common actuation technology in non-wearable applications, they are currently mainly rigid, and their physical size and shape are often limited by the constraints of a molding or die-based manufacturing process. Even flexible TEG devices are typically only capable of flexing in one direction at a time.

Three-dimensional conformable actuating technologies offer better potential for conductive heat transfer due to improved contact area with complex surfaces. They are also more comfortable to wear. Textiles are a logical platform for thermal actuation in on-body technologies, and resistance-based

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heating is the most common actuation mechanism in this space due to its potential for fabrication in fiber- or yarn-form. Many existing textile-based actuation approaches focus on actuator fabrication at the textile stage: typically by weaving, knitting, or laminating the actuating filament into a non-conductive textile structure [5]. The resulting textile is then integrated into a product. In the case of clothing, this poses a design challenge because the actuating filament typically must be continuous to provide evenly-distributed heat. The cut-and-sew processes that are most common to garment design and fabrication pose a challenge for textile-integrated actuators, since the actuator path must be designed in concert with the garment pattern (and these two roles are commonly performed by different parties, often geographically dispersed).

Stitched methods offer a relatively large range of adaptability, in contrast to rigid devices or even woven/knitted textile actuators, as the conductor can be laid in at almost any stage in the garment fabrication process. However, stitched methods for thermal actuation are relatively under-explored.

Actuator Design

The actuating filament in the stitched architecture implemented here is silver-coated Liberator40® conductive fiber (Sysco Advanced Materials, Inc.) that has a VectranTM core (Kuraray Co. Ltd.). The VectranTM core is more stable to higher temperatures than most fibers used in apparel production, enabling it to withstand the temperatures produced when the textile is active. The silver yarn is used as the bobbin thread (with generic polyester sewing thread in the needle) in a Brother BAS-342G Industrial Sewing Machine (Programmable Electronic Pattern Sewer). This machine forms a lockstitch structure, and the direction of stitching is controllable in 2 dimensions. To produce a heating textile, it was stitched in a serpentine pattern onto a fabric substrate (as seen in Figure 1).

In initial bench testing [6] we explored the effects of trace thickness (number of stitched passes), trace spacing (distance between passes), and fabric substrate properties (fiber content and presence or absence of a covering layer) on the temperatures produced at different power levels. A direct current (DC) power supply was used as a power source to the swatches for heat generation, and negative temperature coefficient (NTC) thermistors (10kΩ, TDK Corp.) were used to record sample temperatures. The results of these bench tests showed that the actuating swatches each displayed a linear power/temperature response [6], the slope of which was affected by all of the variables tested. Fiber content of the fabric structure was the only variable that showed negligible effect on the temperature/power relationship. The best actuator design for our purposes showed the most temperature change per Watt, the most consistent heat distribution, the best heat retention under the swatch, and good extensibility/recovery characteristics (for 3D conformability).

Based on these bench test results, the implementation of the actuator in the garment structure used an elastomeric knit fabric base layer and cover, and a single-trace serpentine pattern stitching with a line spacing of 0.4cm.

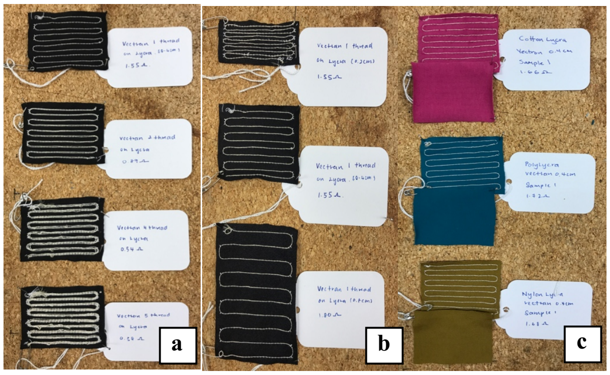

Figure 1: Actuator swatches showing (a) variable trace width (b), trace spacing (c), and fabric substrate properties [6].

Garment Design

Our focus in garment development was on the design of a garment that could effectively deliver supplemental heat to the fingers, but still remain wearable for long-term, everyday indoor activities. Because the wrist and hand have many blood vessels that sit close to the surface, the garment design aimed to leverage this fluid circulation as a thermal transport mechanism to deliver heat from more proximal areas (that are easier to access and more comfortable for long-term coverage) out to the distal fingertips. In parallel, this design implementation served to enable pilot evaluation of the relationship between generated heat and experienced temperature change in a wearable heating system. The body serves as a sink that affects to varying degrees the amount of temperature change at the surface. If the surface thermoreceptors are controlling perceived experience, the temperatures experienced by those receptors is an important variable to account for in system design (and the variability between subjects in thermal transport must be measured to inform that design).

To explore heat delivery to the full hand, we implemented two variants on wrist and hand heating: a wrist-only actuator (heating the circumference of the wrist), and a wrist-and-hand actuator (heating the circumference of the wrist in addition to the palmar and dorsal surfaces of the hand below the phalangeal joints). An extendable fingerless cuff (Figure 2) was developed for emphasis on everyday usability. This specific form of hand covering is a cuff style already found in many long sleeve shirt or jacket designs. It is also a relatively stable apparatus that may be folded into a shirt to deliver heat to the forearm or worn around the hands to deliver heat to the body of the hand. Two separate heat-actuating pathways were created on the extended cuff garment: (1) Front to back of wrist and (2) Front to back of hand (Figure 2). The heat-actuating pathways are separated such that separate parts of the hand can be selectively targeted with the thermal stimulus. Snap connectors are used as electrical connections to the power supply for each actuating pathway.

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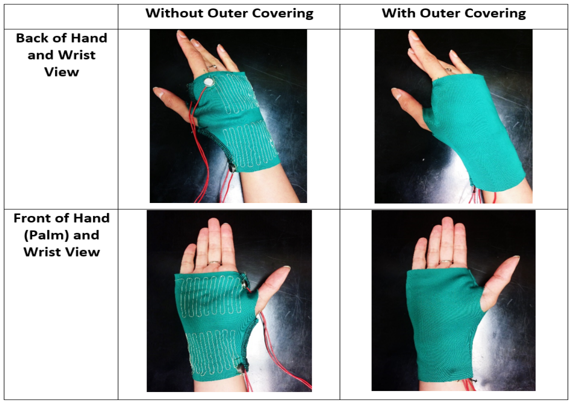

Figure 2: Garment Design: (Left) Inner lining of stitched resistive heating elements with (Right) Mylar insulation and additional polyester-spandex knit outer layer.

As seen in Figure 3, the garment itself was also designed to increase heat retention and prevent radiation to the environment. A separate covering of the same fabric is worn over the layer containing the heating elements, and a heat-reflective foil layer (Foil Mylar, Primacare) was inserted between the two garment layers.

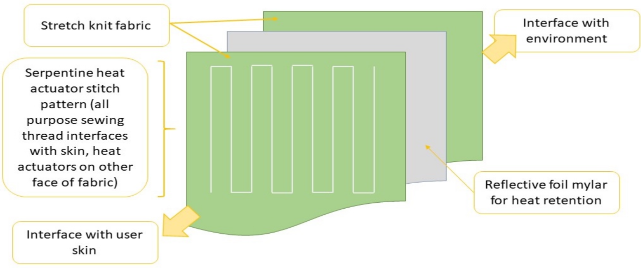

Figure 3: Garment fabric layers schematic.

To understand the rate of temperature change in the glove, we conducted a benchtop test in which power was supplied at a constant rate and temperature was measured over time. From Figure 4 we can see that for each power input, the temperature stabilizes at approximately 300 seconds (5 mins).

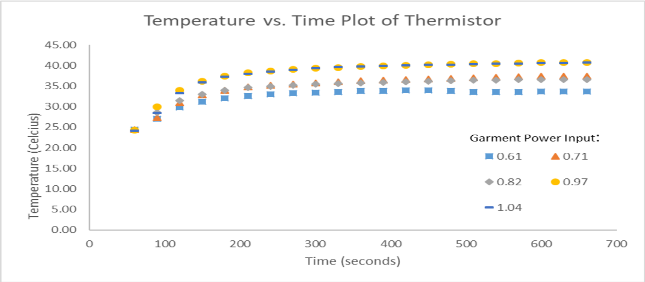

Figure 4: Temperature over time at constant power(W).

Pilot User Study

Characterizing the textile and garment on the bench provides primary performance data, but because the actuator must function in a thermal system that includes the human body, it must also be characterized on the body in order to understand the relationships between power/heat output and temperature experienced by the skin. Therefore, a pilot user study was conducted to collect initial data from human users. The test was conducted in a thermal chamber, measuring 12’6” x 7’6” x 7’0”, to control for environment temperature and humidity. To reduce variability in full-body clothing insulation between participants, each participant wore the same long-sleeve shirt in their size and long jeans. Six participants (3 males and 3 females, with an age range of 21-30 years old) participated in the study in a cold, 18°C environmental condition.

Seven test conditions, each five minutes, were conducted in random order, as shown in Table 1. Temperature conditions included: 33°C (mean neutral skin temperature), 37.5°C (midpoint between neutral and pain threshold), and 40°C (slightly lower than the mean pain threshold of 42°C) [7].

Table 1. Test Conditions.

Heat Location	Garment Temperature		
Wrist	1) 33°C	2) 37.5°C	3) 40°C
Wrist and Hand	4) 33°C	5) 37.5°C	6) 40°C
7) No Heating			

The garment was warmed five minutes prior to donning in each condition to allow for stabilization. The modulation of temperature was done by varying the current passing through heating elements using a DC power supply (Dr. Meter HY 3005F-3) with a fuse (1A current rating, Schurter Inc.) to provide overcurrent protection.

NTC thermistors (10kΩ, 1% Disc, TDK Corporation) were used to record skin and ambient temperatures through a NI-USB 6001 data acquisition system. The skin-temperature thermistors were attached to each participant using medical tape. After donning the warmed garment, skin temperature data from the participant’s fingertip, back of hand, palm, back of wrist, and wrist, were collected continuously to measure the heat that was being transmitted to the skin. Throughout each five-minute test condition, the participants remained seated and inactive, with their right hand placed flat on a desk. At the end of every test, a thermal camera (FLIR C2TM) was used to capture the heat distribution in each test condition.

RESULTS

Pilot User Study

Participants’ physiological responses to thermal stimuli in the form of quantitative data gathered from thermistor results, is presented. Figure 5 shows the mean and standard deviation of temperatures experienced at the skin in each thermistor location (ventral and dorsal wrist, palmar and dorsal hand) in each garment temperature condition.

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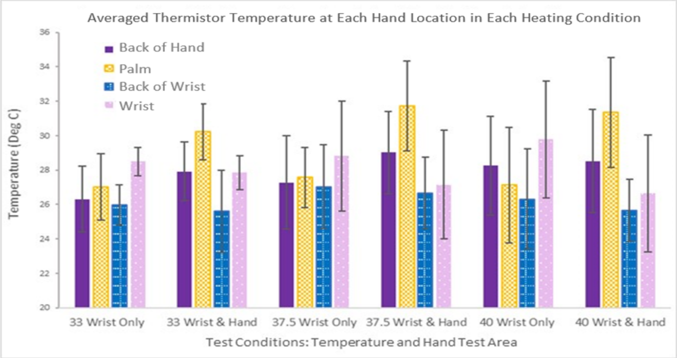

Figure 5: Averaged thermistor temperature at each hand location in each heating condition.

Figure 6 shows the temperature difference between the temperature collected in each test condition, from the back of hand, back of wrist, palm, and wrist (front) thermistors as compared to each participant's temperatures in each respective location in the no active garment heating test condition (i.e. ΔT = Skin temperature at test condition – Skin temperature at no active heat). The difference was calculated for each participant, and then averaged in order to find the standard deviation for the average difference in temperature. Positive numbers indicate an increase in skin temperature compared to the no active heating condition, and negative numbers indicate a decrease in skin temperature compared to the no active heating condition. Temperature difference for all four thermistor locations are presented in the graph.

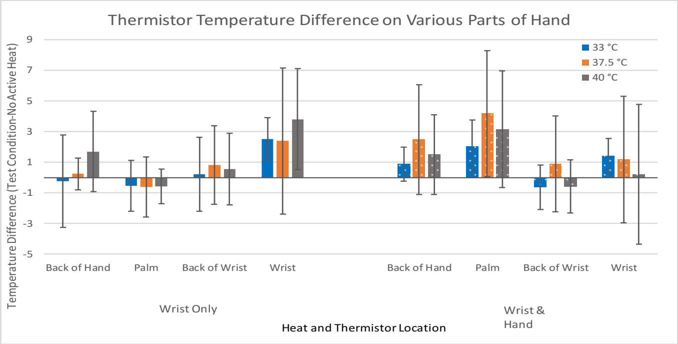

Figure 6: Averaged thermistor temperature difference on various parts of the hand compared to no-heating condition.

Figure 7 displays the average fingertip temperatures in each garment and chamber temperature. Figure 8 shows the thermal heat distribution of the thermal garment for each test condition. Data from only one participant (female, age 24) is shown in Figure 8.

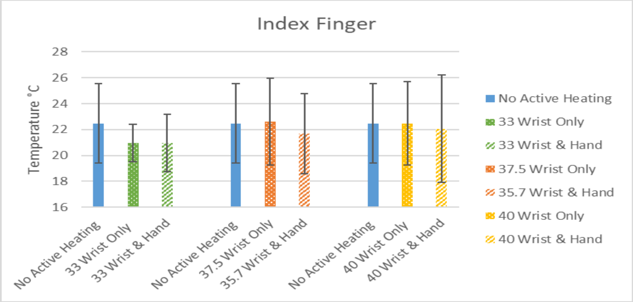

Figure 7: Avg. thermistor temperature for the index finger.

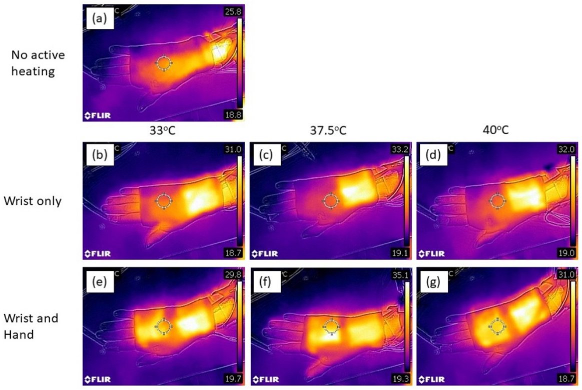

Figure 8: Thermal images for one participant for each test condition. (a) No active heating, (b)-(d) wrist only heat, (e)-(g) wrist and hand heating. Note differences in scale values presented on the right as a vertical bar.

Garment vs. Skin Temperatures

As seen in Figure 5, temperature at the skin varied considerably from the garment's characterized temperature. With the garment at 33°C, directly beneath the heated area the skin experienced an average of 25.97°C at the back of wrist and 28.49°C at the front of the wrist in the wrist-only condition, compared to 25.60°C back and 27.85°C front in the wrist-and-hand condition. The palm experienced 27.01°C in the wrist-only condition and 30.22°C in the wrist-and-hand condition, and the back of hand experienced 26.31°C in wrist-only and 27.91°C in the wrist-and hand.

When garment temperature increased to 37.5°C, the skin experienced an average of 27.03°C at the back of wrist and 28.82°C at the wrist in the wrist-only condition, compared to 26.65°C back of wrist and 27.16°C front of wrist in the wrist-and-hand condition. The palm experienced 27.27°C in the wrist-only condition and 27.57°C in the wrist-and-hand condition, and the back of hand experienced 29.02°C wrist-only and 31.72°C wrist-and hand.

With the garment at 40°C, the skin experienced an average of 26.31°C at the back of wrist and 29.78°C at the wrist in the wrist-only condition, compared to 25.65°C back and 26.64°C front in the wrist-and-hand condition. The palm experienced 28.26°C in the wrist-only condition and 27.12°C in the wrist-

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and-hand condition, and the back of hand experienced 28.53°C wrist-only and 31.35°C wrist-and hand. The standard deviation of these averages ranged from 0.83°C to 3.40°C, showing a high variability between subjects.

When compared to the skin temperatures experienced by each subject in the no-heat condition (Figure 6), similarly inconsistent patterns are observed. Importantly, conditions were randomized in this trial. While each participant experienced a 5-minute stable period between conditions, the effect of supplemental heating in prior trials may have affected no-heat baseline measures in addition to inter-subject variability in thermal set points. Therefore, this approach to baseline temperature collection may not be the most effective means of normalizing skin temperature responses.

Heat Transfer to The Fingertip

While the temperatures experienced at the skin during active heating are affected by heat flux to the body, the temperatures of body areas further from direct heating are more dramatically affected by body thermoregulatory processes. The fingertip, in particular, experiences more drastic thermoregulation through vasoconstriction and vasodilation, and these circulatory responses vary considerably across subjects. As seen in Figure 7, fingertip temperature response showed strong variability between subjects and across conditions. Clear relationships between warming conditions and fingertip temperature were not observed in this study. However, it is important to bear in mind that the very small participant pool is likely to have influenced these results, and it is possible that more stable trends may be observed in a larger participant pool. Further, a closed-loop self-regulating system that modulates garment temperature based on skin temperature would allow for control of the skin temperature experience to better evaluate its relationship with fingertip temperature.

CONCLUSION

The combined bench and human pilot test results from this study have shown that the stitched method of producing textile-based actuators can provide consistent, controllable warming within a garment structure. The textiles produced look and feel very similar to everyday clothing and textiles, and offer the same mechanical properties and 3D conformability of 4-way stretch textiles. However, when that garment is applied to the human body, variability, in tissue, circulation, and thermoregulatory responses, results in considerable variation in the temperatures experienced at the skin surface beneath the garment as well as in more distal extremities.

Based on the principle that thermal experience is dominated by temperatures experienced at the most distal extremities, controlling the variability in temperatures experienced at the skin surface appears necessary to fully characterize the effect of supplemental heating to the hands and wrist on fingertip temperature. Future work will focus on developing closed-loop, sensor-driven control of garment temperature, in order to standardize the temperatures experienced at the skin surface. In that manner, effect on distal thermal transfer can be more accurately characterized.

ACKNOWLEDGMENTS

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