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CHARACTERIZING HYBRID ACTIVE/PASSIVE HEATING SYSTEMS FOR THERMAL MICROCLIMATE CONTROL

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ABSTRACT

Heating devices offer particular benefits in cold climates and to those with thermoregulatory or vasospastic disorders, like Reynaud's syndrome. Heating devices can be used to moderate a wearer's microclimate to alleviate thermal discomfort and pain, especially in the distal extremities where thermal sensitivity is the highest. Applying insulation on top of wearables with heating components can reduce both heat lost to the environment, as well as power needs for maintaining thermal comfort. Here, we evaluated one stitched, heated textile garment with eight textile insulation materials to assess heat propagation (measured by five thermistors on a mannequin hand and one in the surrounding, enclosed environment) and wearability (measured from tests of fabric weight, thickness, flexural rigidity, and permeance). Results find energy conserved by all materials, but wearability drawbacks for some strong insulators. Thicker materials generally had higher insulative properties, and reduced heat propagation to the indirect heating regions, specifically the finger and thumb. Additionally, heat propagation through to the environment was stronger than to the finger and thumb.

Keywords: Wearable technology, textiles, heating

1. INTRODUCTION

Wearable heating technologies are uniquely positioned to provide continuous, personalized modulation of the individual microclimate. On-body thermal control may offer substantial energy savings, while allowing co-occupying users to control their microclimates independently [1-2]. Heating devices in particular offer advantages in cold climates and indoor spaces, where comfort, performance, and dexterity are degraded as the temperature of one's extremities are reduced [3]. Supplemental heating is needed for a wide variety of medical conditions, including thermoregulatory disorders, Reynaud's syndrome, mild musculoskeletal injuries, pain management, and prevention of cold-induced injuries like frostbite.

However, on-body heating devices are often restricted by actuator power requirements. Conserving body or supplemental heat through garment design and insulation can mitigate power requirements, but often presents tradeoffs between thermal efficiency and wearability considerations. Here, we focus on providing supplemental heat with Joule heating (following actuator development established in [4], and explore the propagation of this heat within and through 3D wearable systems with different material properties. Wearability of each material is evaluated in comparison.

2. MATERIALS AND METHODS

Heated glove prototypes similar to [5] were manufactured. The heating element (Syscom Liberator 40® silver-coated Vectran™ thread) was applied to the surface of a polyester-

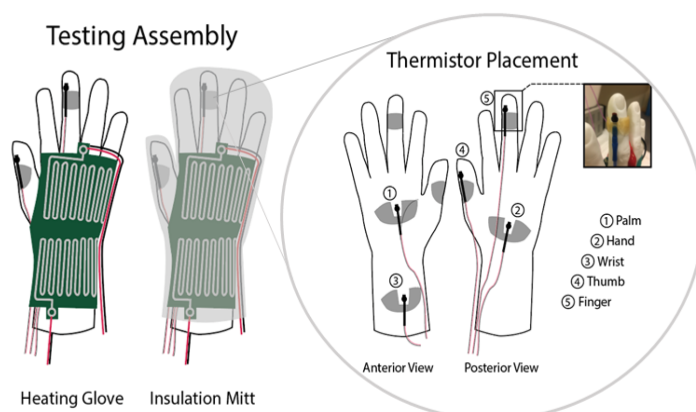

FIGURE 1: PROTOTYPE DESIGN AND SENSOR LOCATIONS.

spandex knit textile using a CAD pattern stitching machine (Brother BAS342G), according to the results of an earlier characterization study [4]. Insulating mittens covering the fingers were fabricated to provide an enclosed airspace with areas close to the heating element as well as isolated from the element in order to measure propagation within the system (Figure 1). Eight different commercially available materials were selected as insulation candidates based on their known advantages as insulators: (1) Scuba Knit (93% polyester, 7% spandex), (2) Polartec® Regulator Fleece (info. unavailable; likely 100% polyester), (3) Polartec® 100 Microfiber (100% polyester), (4) Polartec® 200 (100% polyester), (5) Neoprene 0.5mm thickness (outer: 100% nylon, inner: 100% synthetic rubber), (6) Neoprene 1mm thickness (outer: 100% nylon, inner: 100% synthetic rubber), (7) Thinsulate™ (insulation: 55% polyester 45% olefin; outer: 100 olefin), (8) Mylar (100% aluminum). Each glove-insulation combination was fitted over a mannequin hand. The experimental setup is shown in Figure 2, where the glove was powered to 0.5A with a DC power supply. 10kΩ NTC thermistors (Vishay BC Comp.) were used to measure temperature in six locations. Palm and wrist thermistors were directly under heating elements; the back hand thermistor was between heating elements; thumb and finger thermistors were under insulated materials but not directly heated; and ambient temperature was measured with a thermistor attached at the top of the test environment--a covered 12” by 17” by 14.5” Styrofoam cooler (to maintain a controlled environment). Five

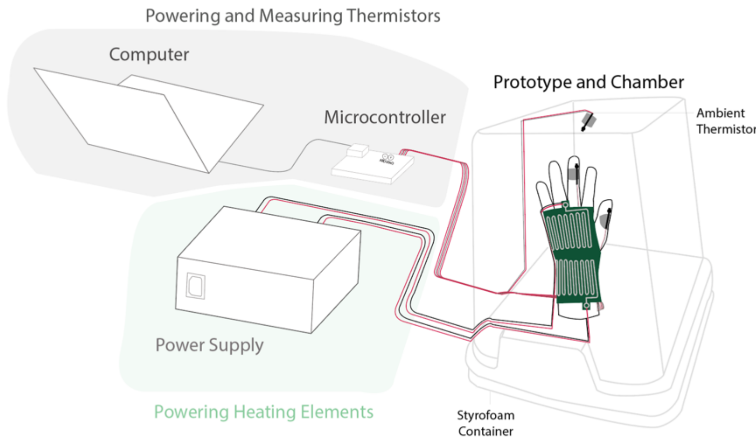

FIGURE 2: EXPERIMENTAL SETUP.

heating trials, each lasting 10 minutes, were repeated for each sample. The system was designed to deactivate the heating elements when a single thermistor reads a value over 40 C (to avoid discomfort or pain for human subject usage). The results from the thermal tests were interpreted with respect to the relationship of the thermistor to the heating element (direct, indirect, or ambient).

Four wearability-related variables were assessed with ASTM standard test methods: (A) Fabric Weight, (B) Thickness (ASTM D1777 with 0.6psi pressure), (C) Rigidity (derived from ASTM D1388 cantilever test), and (D) Permeance (derived from water vapor transmission rate (WVTR) ASTM E96/E96M) [6-8]. Note: stiffness could not be assessed for Mylar due to its tendency to curl.

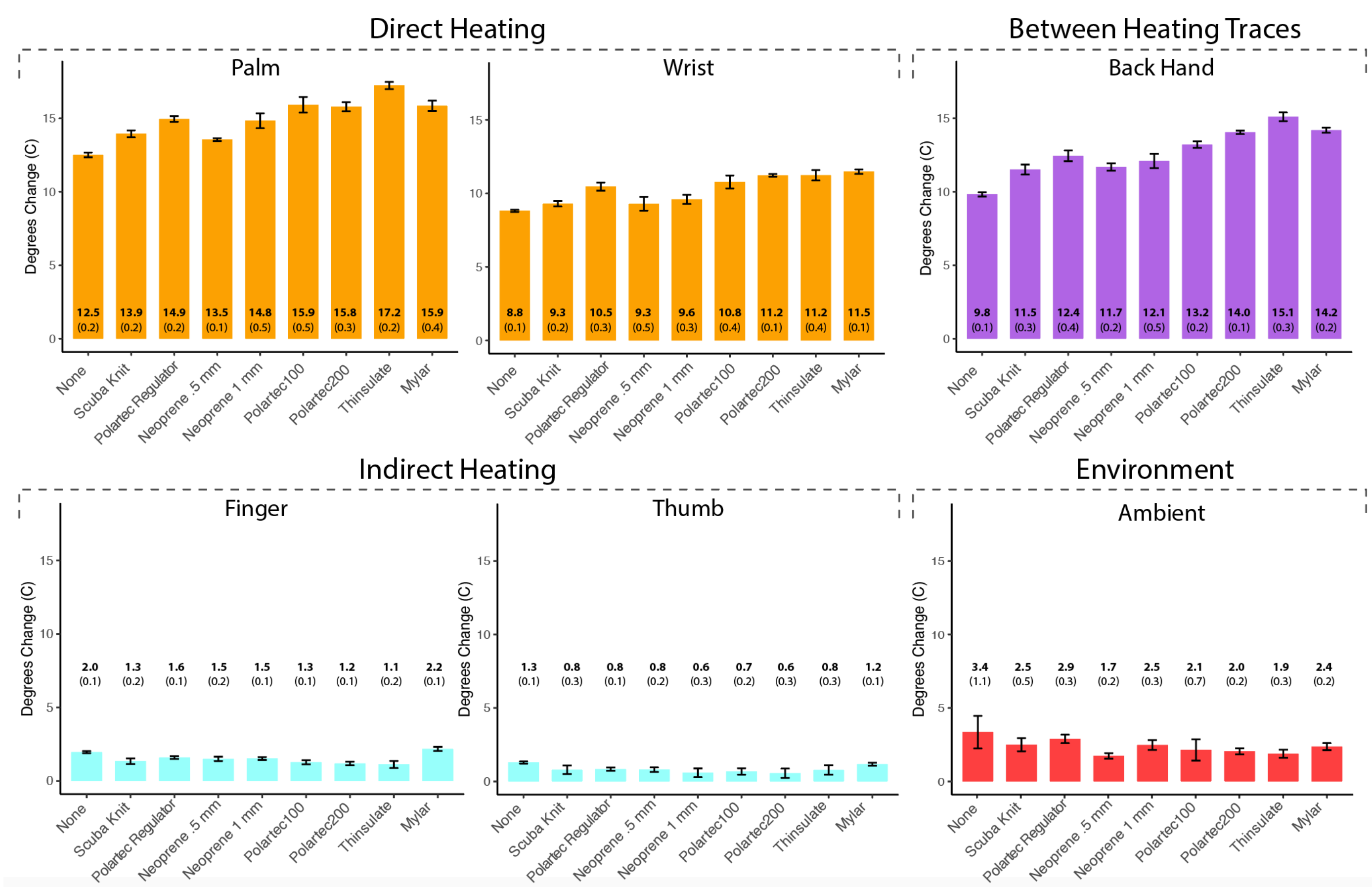

FIGURE 3: HEATING TEST RESULTS.

TABLE 1: WEARABILITY TEST RESULTS. **Material Property Trials**

Material	(A) Fabric Weight (g/m^2)	(B) Thickness (mm)	Bending Length (cm)	(C) Flexural Rigidity (g*cm)	WVTR (g/ h*m^2)	(D) Permeance (WVTR/Δp)*
Scuba Knit	337.04 (13.09)	0.91 (0.02)	1.48 (0.05)	73.85 (2.72)	24.87 (1.89)	1.89 (0.20)
Polartec Regulator	175.94 (2.40)	1.03 (0.02)	0.5 (0.16)	4.49 (1.40)	27.38 (5.31)	5.31 (0.37)
Polar100	138.85 (3.49)	0.89 (0.12)	1.69 (0.08)	39.68 (1.97)	25.11 (3.70)	1.91 (0.21)
Polar200	252.08 (6.20)	1.92 (0.01)	2.02 (0.11)	102.92 (5.83)	24.01 (1.83)	3.55 (0.20)
Neoprene (.5 mm)	368.14 (10.32)	1.25 (0.01)	1.60 (0.14)	94.39 (8.43)	2.43 (1.71)	0.18 (0.12)
Neoprene (1 mm)	359.22 (5.88)	1.41 (0.01)	2.71 (0.08)	263.87 (8.13)	2.38 (1.73)	0.18 (0.13)
Thinsulate	175.20 (15.17)	4.11 (0.06)	4.47 (0.36)	350.53 (28.93)	24.52 (3.51)	1.87 (0.21)
Mylar	14.49 (0.38)	0.03 (0.00)	--	--	1.30 (0.92)	0.10 (0.07)

*Δp = vapor pressure difference

3. RESULTS AND DISCUSSION

Mean heat propagation test results (ΔTemp, representing the difference between T_{final} and $T_{initial}$ at each thermistor location) and standard deviations across 5 repetitions are presented in Figure 3. The palm and back hand ΔTemp were larger than the wrist, likely because the wrist heating elements were lower and closer to the opening. Interestingly, the ambient ΔTemp was larger than the thumb and finger; this might imply that more heat was being transferred through the insulation layer to the environment than within the enclosed airspace of the mitten. Overall, the presence of insulation increased ΔTemp compared to control, i.e., all materials were effective in retaining heat. In the best-case, Polar 100 prevented 1.7 degrees of heat transfer to the environment. However, the degree of increase was different depending on the insulation material. In terms of direct heating (to the hand, palm and wrist thermistors), the Neoprene, Thinsulate™, and Mylar were the top performers, with a range of 10.8 - 17.2 °C increases at these locations. Interestingly, when looking at indirect areas on the hand, using no mitt and Mylar were top performers for temperature increases, although the increases for the finger and thumb were much lower than direct heating regions (between .6 - 2.2 °C). Thicker, more insulative materials may reduce heat transfer inside a clothing system to isolated areas.

The material wearability test results (average values and standard deviations with five samples) are shown in Table 1. As a result of the diversity in materials, material wearability in each category varied greatly. For fabric weight, a range of 14.49 - 368.14 g/m^2 was found, with the lower limit (14.49 g/m^2) belonging to Mylar. Although Mylar and Thinsulate performed well as thermal insulators for direct heating regions, both had extreme wearability measurements compared to other materials, specifically from a high thickness (4.11 mm) and flexural rigidity (350.53 g*cm) for Thinsulate, and a low WVTR (1.30 g/h*m^2) and permeance 0.10 (WVTR/Δp) for Mylar. The Scuba knit, Polartec Regulator, Polar100, Polar200 and even the Thinsulate had favorable vapor transport values, ranging between 24.01-27.38 g/h*m^2, with the highest value from the Polartec Regulator. To translate these results into design decisions, the specific design context (including body area, garment type, and use environment) must be taken into account. Characterization of candidate materials on multiple parameters allows design tradeoffs to be navigated for the use case, as well as presenting opportunities for design innovation. Increasing customization techniques (for example, having an interchangeable insulation layer) could create a device suitable for both thermoneutral environments (using a lighter, more breathable material), and cold climates (where a denser, less breathable material could be used).

Although wearability considerations limit the utility of some strong insulators, insulating active heating garments has a clear energy benefit. While the difference in temperature between the best-case insulation and the un-insulated control condition in these trials is only 1.7 degrees, this is a perceptible difference in experience, and could represent the difference between uncomfortable and neutral or comfortable [9]. However, propagation to isolated areas may not be strong. This is a concern for wearable systems such as clothing, where the aim is to deliver a more uniform thermal experience over the surface of a complex body geometry. It is not always feasible to distribute a heating element over the entire surface, so propagation from the element to more remote areas is desirable. At the same time, it is important to remember that the mannequin test is inherently limited: it does not reflect the influence of body thermal transport systems or body movement. For the question of delivering indirect heat, body posture and movement can both support and limit this transfer, depending on context. Similarly, conduction and transportation of heat through vascular systems can help distribute heat more evenly but will also result in removal of heat from the target area to other body areas.

4. CONCLUSION

Results from this evaluation should be compared to a similar trial performed on human participants. Human trials were not possible due to disruptions caused by COVID-19, but follow-up human trials may determine differences in heat transfer throughout the enclosed system as well as outside of the system. Importantly, because human systems are so variable between participants, mannequin trials are necessary in order to contextualize human results. The results presented here reflect thermal transport through a hand-shaped 3D environment, independent of the influence of human physiology and tissue.

ACKNOWLEDGEMENTS
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