Toward the Development of Customizable Textile-Integrated Thermal Actuators

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Abstract
This study explores efficient methods for production of customizable heated textiles. An electrical heating system using the Liberator40® conductive fiber, stitched in a serpentine pattern on stretch knit fabrics, was employed. Parameters including thread layers, pattern sizes, and different fiber-based substrates and covering were compared when analyzing resistance and temperature output. Results indicated that covered knit fabrics stitched with a 0.4cm serpentine spacing produced the most efficient measure of temperature.

Author Keywords
conductive textiles; conductive yarn; e-textiles; smart textiles; thermal actuation; wearable technology.

ACM Classification Keywords
H.1.2 User/Machine Systems: Human Factors

Introduction and Background
Garment-based heat actuators can be achieved with many mechanisms: including exothermic chemical reactions; air/liquid flow; or phase change materials (PCM) [1][2]. However, most are based on electrical systems (resistance in an embedded conductor or a thermo-electric generator, TEG). Resistive heating affords more textile-like flexibility and coverage than

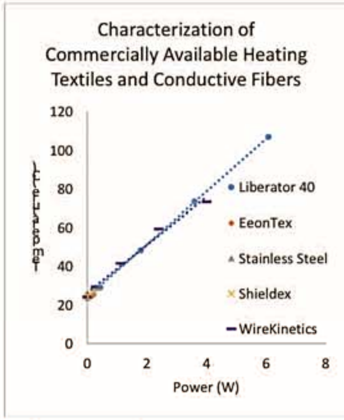

Figure 1: Characterization test of available solutions

Figure 2: Swatches depicting different thread layers (top to bottom: 1 layer, 2 layers, 4 layers and 5 layers)

rigid, small-area TEGs. Conductive yarns or fine-gauge wires can be woven, knitted, or stitched directly to a textile surface [3-5]. We performed initial characterization tests with commercially-available heating textiles and fibers (WireKinetics Ultra Heating Fabric, Shieldex®, stainless steel yarns, EeonTex™), the results of which are shown in Figure 1 (The selected yarn for this study is also included). With these materials, conductive fabrics are restrictive in the geometry and layout of the heating element. Stitched conductors are perhaps the most adaptable method of actuator layout, as they can be used with stretch or non-stretch fabrics and allow the actuator pathway to be laid in any orientation and area. However, many stitch-able conductive threads are not able to withstand the current and temperature of resistance heating. Pilot tests with common silver-coated Nylon (Shieldex®) and stainless steel yarns showed the yarns disintegrated under the current load. Therefore, Liberator40® conductive fiber (Sysco Advanced Materials, Inc.) was used. The silver-coated core of Liberator40® is made of very strong Vectran™ (Kuraray Co. Ltd.) fiber, which can withstand much higher temperatures than Nylon.

Thermal Actuator and System Parameters

A Brother BAS-342G Industrial Sewing Machine was used to sew conductive traces on fabric swatches with Liberator40® in the bobbin thread and regular sewing thread in the needle. The stitch was oriented in a serpentine fashion for even heat distribution. Several parameters important to the development of customizable textile-integrated thermal actuators were investigated: number of thread layers, spacing between serpentine-configured conductive traces, fabric type and fabric covering.

A DC Power Supply (Dr. Meter HY3005F-3) was used as a power source to the swatches for heat generation. NTC Thermistors (10kΩ, 1% Disc, TDK Corporation) were used to record sample and ambient temperature through an NI USB-6001 data-acquisition system.

(1) Thread Layer

We explored increasing the number of stitched Liberator40® threads in a parallel configuration, to measure effects on heat generation and distribution. Four Liberator40® conductive thread layers were investigated: 1, 2, 4, and 5 layers. The serpentine configuration was 5cm and 0.4cm wide at every turn (total 9 turns) (Figure 2), stitched onto a 6 by 4.5cm nylon spandex swatch. Current was recorded at 0.5V increments from 0V-4V (or when samples began to smoke). Resistance values for each of the swatches are shown in Table 1. A thermistor was placed under the swatch (non-conductive face that would interface with the skin) to record temperature. Ambient temperature was not controlled (room temperature, indoors).

Data Analysis and Results

Thermistor temperature data was collected after 1.0 minute of normalization for each voltage increment at ambient temperatures between 23.2 to 24.2 ^{o}C. From Figure 3, we can see that the number of thread layers is inversely proportional to the efficiency of the system (characterized by the slope; greatest temperature increase for given power increase). Comparing this to resistance data (Table 1), whereby an increase in the number of thread layers corresponded to a decrease in resistance values of the samples, the drop in resistance with increasing thread layers means more current is needed to generate the same temperature effect as a sample with fewer threads. Although the 2- layered systems yielded higher temperatures than all other

Trace Layers	Resistance (Ω)
1	1.55
2	0.89
3	0.54
4	0.38

Table 1: Resistance of samples with different thread layers

Figure 4: Swatches depicting different spacing of thread (top to bottom: 0.2 cm, 0.4 cm, 0.8 cm)

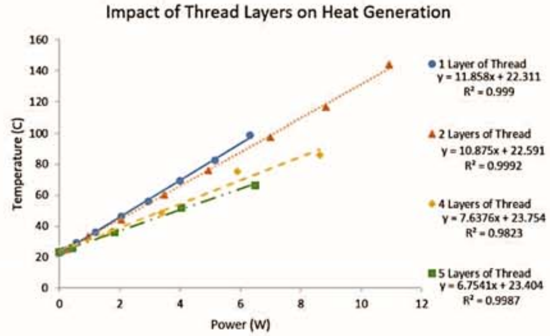

Figure 3: Results for varying thread layers

combinations, the efficiency was comparable to 1 layer, but would add manufacturing complexity. Therefore, 1 layer of thread was selected for future tests.

(2) Spacing of Thread

The goal of this test was to determine an optimal serpentine configuration (by modulating the thread spacing) that would allow even heat distribution. Here, the serpentine configuration is a constant 5cm length with a varied width at every turn (total of 9 turns) (Figure 4). Three turn widths were investigated: 0.2cm, 0.4cm, and 0.8cm. The swatch size in this case varied depending on the total width of the varied spacing. Samples were tested with the same method as the previous test. In addition, heat distribution of the samples were evaluated qualitatively using a thermal camera (FLIR C2™).

Data Analysis and Results

From Figure 5, we can see that 0.4cm spacing yielded a system that is the most efficient, while the 0.2cm spacing was very similar in efficiency compared to the 0.4cm spacing. When thermal distribution was investigated from the thermal images (Figure 6), we found that 0.2cm spacing sample had the best thermal distribution, followed by the 0.4cm and 0.8cm sample. However, 0.2cm spacing was determined to be undesirable in terms of cost and manufacturability as the decrease in size did not give rise to a much higher efficiency. Therefore, 0.4cm spacing was selected as the standard used for future tests.

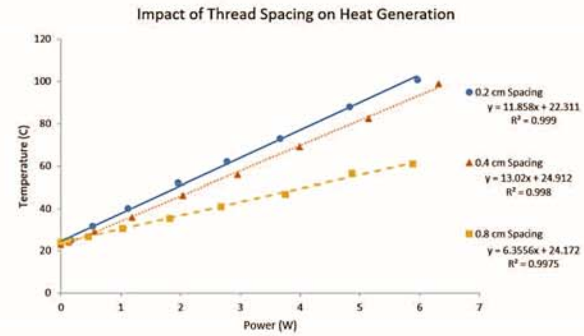

Figure 5: Results for varying thread spacing

(3) Fabric Type and Fabric Covering

An important consideration for creating textile-integrated electronics is insulating conductive traces from the skin. The goal of this section is to determine if there are varying effects of different fabrics and fabric covering on heat dissipation. Three different knit fabrics were used: cotton-spandex, polyester-spandex, and nylon-spandex (Figure 7). The 1 thread layer and 0.4cm trace spacing parameters were used, stitched on 6 by 4.5cm swatches of each fabric. A fabric covering (same fabric as the sample) was placed above the exposed conductive trace for the covered condition, and the uncovered condition was used as the control. As before, a thermistor was placed below the fabric layers. Samples were tested with the same method as previous tests.

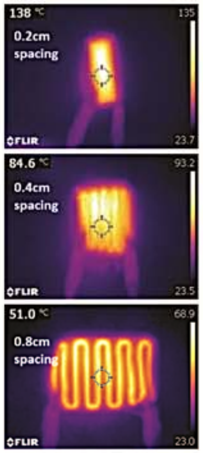

Figure 6: Thermal Images for varying thread spacing at 3V

Figure 7: Swatches depicting different fabric types (top to bottom: cotton-spandex, polyester-spandex, nylon-spandex)

Data Analysis and Results

Figure 8 shows that there were no huge differences between the fabrics for the covered version, but there were slightly larger effects for the control. Comparing across fabrics, the polyester-spandex fabric had the largest difference in temperature for the covered and uncovered conditions, which we speculated was due to difference in thermal conductivity (hence heat retention) of the substrate fibers. However, fiber thermal conductivity values from literature do not support our results [6], so result differences are likely due to effects of differences in fiber/yarn or knit structure. Regardless, in all cases, the fabric covering retained heat much better than the control as shown by the collected data.

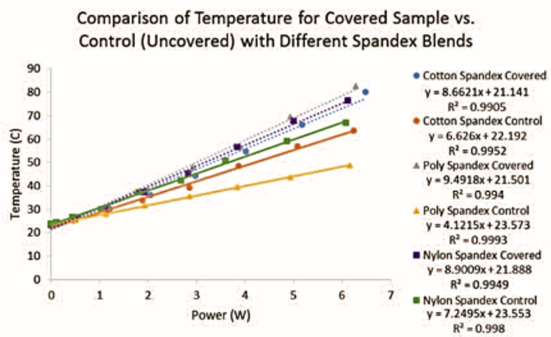

Figure 8: Results for each fabric (same marker shape) and fabric covering (dotted line: covered, solid line: control)

Discussion and Future Work

This study investigated thread layers, pattern sizes, and fiber-based substrates for the development of customizable textile-integrated thermal actuators. By using Liberator40® conductive fiber as the heating element arranged at a 1-layered, 0.4cm serpentine spacing with covered substrate for further heat retention, we present a possible solution to a customizable heated textile platform that is more efficient at heat generation than what is commonly used. When compared to the same applied power from other studies, our solution gives much higher heat generation ranges, providing greater modulation ability. Future work includes increasing sample sizes, investigating the role of substrate fiber content, varying stitch configuration, and working towards the development of an on-body heated garment solution that is customizable, functional and safe for use.

Acknowledgements

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