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Design considerations of Peltier-Integrated Therapeutic Wrist Wrap for Medical Applications

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***Abstract*—Muscle soreness, joint injuries, and chronic joint conditions are prevalent, often hindering daily activities due to debilitating pain. While numerous thermal-based devices exist for pain management, user control and combined cooling and heating capabilities are commonly lacking. This research introduces an Integrated Therapeutic Wrap, utilizing the Peltier effect to deliver both cooling and heating treatments for injured and chronically affected joints, such as the wrist. Proposed design allows switching between cooling and heating mode, comprising of multi-layered arrangement to optimize heat transfer, storage, and insulation. The design's thermal management and the thermal characteristics of the Peltier elements and their configurations are examined. Strategies for Peltier device-based temperature regulation and a thermal management technique are developed to enhance the wrap's cooling efficiency. Thermal imaging confirms the system's effectiveness in providing both cooling and heating therapy.**

***Index Terms*—Flexible Peltiers, Thermoelectric Devices, Reversible heating-cooling,**

I. INTRODUCTION

Around 8.6 million people annually suffer from sports related and other types of muscle injuries. The most prevalent being swollen muscles, strains, fractures and sprains (1). This is typically treated using hot or cold therapy by incorporating devices such as ice packs, icy hot patches (2), microwavable heating pads (3) and electric heating pads(4). These devices usually provide passive heating and cooling and does not always allows both in a controlled manner (5). Recent advancements in active cooling heating with the use of thermoelectric devices have been studied in (6) and (7), using either rigid or flexible packaging.

Here we introduce a Therapeutic Wrist Wrap, as shown in Fig. 1, using Thermoelectric devices known as Peltiers (8). These devices have mostly been used in medical equipment like imaging systems (9) or lasers (10) and have not been implemented in any therapeutic devices. Peltiers allow reversible heating and cooling, however, the main problem with these devices is that they get either too hot or cold making it not suitable to be used in medical applications on its own (11). For example, medical applications require precise and efficient temperature control to enable functioning for long time periods. Too much heat can burn the skin and also compromise the ability of Peltier to efficiently cool down.

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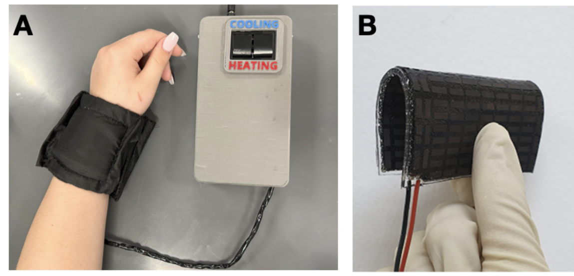

Fig. 1. The proposed Peltier-Integrated Therapeutic Wrist Wrap (A) and flexible Peltier (B)

To overcome this several studies test out the use of various heat sinks.(12) show the use of aluminum heat sinks in different configurations and examine how altering the geometries affects heat transfer.

More specifically, this study implements flexible Peltiers to a thermo-reversible therapeutic wrist wrap and outlines the design considerations of using flexible Peltiers for medical applications by testing performance with other materials.

II. METHODS AND MATERIALS

A. Heat Transfer Analysis Across Different Materials

Our proposed device is made of different layers of materials to enhance the functionality in terms of heat transfer, storage and insulation. In order to analyze the heat transfer across different layers, first we need to model and then the test essential layers of Peltier and materials. For this purpose, thermal properties of the essential layers of our proposed design (as depicted in Fig. 2), such as graphite, a silicone pad (13), and an ACE bandage (14) were analyzed. Utilizing temperature testing data alongside existing information on thermal conductivity, heat capacities, and dimensional properties, models were constructed to compute temperature profiles for each material. Table I outlines the derived data.

Based on (15), the thermal performance of a Peltier can be formulated as:

$$T = -\frac{S_P}{2k_{TP}}x^2 - \frac{C_1}{k_{TP}}x + C_2 \quad (1)$$

where S_p and K_{tp} are heat generation rate per unit volume of the Peltier and thermal conductivity of the thermal pad, respectively. C_1, and C_2 are constants that can be solved based

TABLE I
SUMMARY OF MATERIAL THERMAL PROPERTIES (13; 14)

Material	Thermal Conductivity (W/mK)	Specific Heat Capacity (J/g°C) *approx values	Notes
Graphite	140	0.720	High thermal conductivity
Silicone Thermal Pad	6.0	2.0	Moderate thermal conductivity
ACE Bandage	0.0627	0.07	Low thermal conductivity (insulating)
Peltier Device	N/A	N/A	Heat generation rate: 4.905 x 10^5 W/m^3

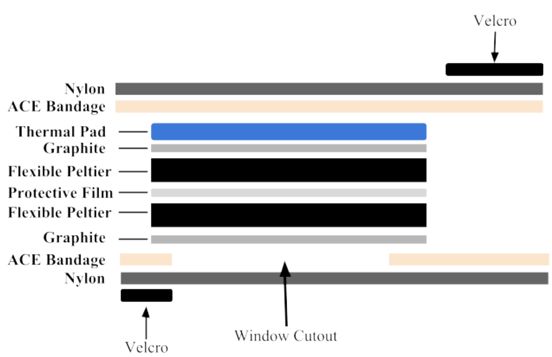

Fig. 2. Layer by layer design of the proposed Peltier-Integrated Therapeutic Wrap

on boundary conditions, and x is the distance into the thermal pad that the heat has traveled ($x \leq W$). Therefore:

$$T(x=0) = T_P \tag{2}$$

$$T(x=W) = T_m \tag{3}$$

$$T = -\frac{S_P}{2k_{TP}}x^2 + \left[\frac{T_m - T_P}{W} - \frac{S_P}{2k_{TP}}W\right]x + T_P \tag{4}$$

This can then be solved with the equation by plugging in the above values from Table I.

$$T = -\frac{4.905 \times 10^5 \mathrm{W/m^3}}{2(6\mathrm{W/mK})}x^2 + \left[\frac{310.85\mathrm{K} - 313.15\mathrm{K}}{0.0015\mathrm{m}} - \frac{4.905 \times 10^5 \mathrm{W/m^3}}{2(6\mathrm{W/mK})}(0.0015\mathrm{m})\right]x + 313.15\mathrm{K} \tag{5}$$

Simplifying equation 5 results in a temperature profile for the Silicone thermal pad and the graphite layer. For the calculation, it should be noted that the thermal conductivity and thickness of graphite are 140 W/mK and 100 μm, respectively, while the temperature of the graphite when the Peltier is heating, will be 307.15 K.

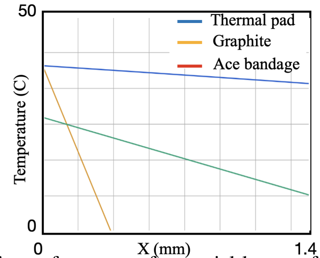

Fig. 3. Heat transfer performance of essential layers of the proposed Peltier-Integrated Therapeutic Wrap

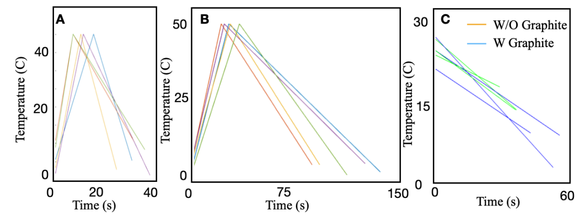

Fig. 4. Peltier heating and cooling times at 40°C (A), 50°C (B) and the effects of adding graphite to the cold side of Peltier (C).

After establishing temperature profiles for the Peltier with the thermal pad and graphite sheet, the study analyzed heat transfer from the thermal pad to the outer elastic bandage to assess its impact on the device efficiency, as:

$$T = -\frac{x^2}{2k_{EB}} + \left[\frac{(T_{TP} - T_{EB})k_{EB}}{W} - \frac{W}{2k_{EB}}\right]x + T_{TP} \tag{6}$$

with thermal conductivity of the elastic band as $K_{EB} = 0.0627W/mK$ and the boundary conditions as: $T_{Tp} = 307.15K, T_{EB} = 305.95K$, while the thickness of the layer is $W = 1mm$. The temperature profile of the thermal pad to the elastic bandage can then be calculated.

The results are showns in Fig. 3. When evaluating the thermal pad at top the heating Peltier device, a modest temperature difference of approximately 3°C is observed between the bottom and top layers of the thermal pad, primarily attributed to its lower thermal conductivity. In contrast, graphite exhibits a significantly larger temperature difference due to its high thermal conductivity and heat capacity. This underscores the strategic use of graphite adjacent to the Peltier, effectively preventing excessive heat accumulation and facilitating the transfer of heat to the thermal pad. Furthermore, the ACE bandage temperature profile indicates that the temperature difference increases, most likely due the the low thermal conductivity or insulating nature. Therefore when assembling materials their thermal properties needs to be considered.

B. Transient Temperature Analysis of Peltiers

In order to identify thermal diffusivity, Peltiers were tested by varying power supply, duration and use of heat sink to observe how the behaviour of Peltiers changes. The 40 mm by 20 mm Peltier was supplied with 2.5 V and a current of 1.225 A and the time taken for the Peltier to reach 40°C was recorded. The results are plotted in Fig. 4. The results show the average time taken to reach the initial temperature of 25°C was about 10 s. To compare another study was done to observe same parameters for 50°C.

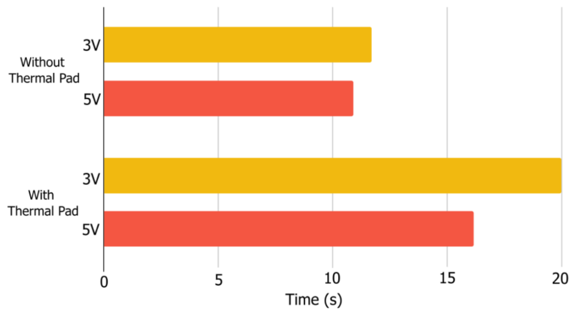

Fig. 5. Cooling time of flexible Peltier with and without thermal management

The addition of graphite effectively prevented the Peltier from overheating for a longer period of time than not applying the graphite. This will allow the Peltier to remain ON for slightly longer periods of time, giving the device time to reach lower temperatures, and sustain these lower temperatures for longer while the Peltier has time to cool down.

Interestingly, the findings suggest that graphite is not an effective heat sink, as it doesn't efficiently dissipate the heat generated by the Peltier. Instead, it serves as a proficient medium to retain the produced heat, enabling brief intervals of turning off the Peltiers to prevent overheating and reduce power consumption.

In conclusion, the graphite sheet is a viable solution when using Peltiers continuously for long periods of time but raises the question of what material can be used as a heat sink in the outer layer of the therapeutic wrap to prevent the hot side of the Peltier from affecting the heat pumping side - the cold side of the Peltier. Potential solutions may include stacking the graphite sheet and observing the effect on heat dissipation or modifying the control system so that the Peltiers do not remain on long enough for overheating to occur.

C. Transient Temperature Analysis of Peltier's with Thermal Management Materials

To address overheating on the cooling side, materials were introduced on the opposite side to enhance heat dissipation. Graphite, chosen for its high thermal conductivity and heat capacity, was applied to the top side of the Peltier, opposite the user-facing side. This is intended to absorb a significant amount of heat before undergoing temperature changes and serve as a heat sink during cooling mode when the opposite side is heating. Additionally, a thermal pad, selected for its lower thermal conductivity but greater thickness compared to graphite, was placed on top of the graphite to further aid in heat dissipation. The first test involved adding a 1mm thick thermal pad to the top side of the flexible Peltier and assessing its impact on the device's cooling capabilities. The results in Fig. 5 indicate that the Peltier sustains cold temperatures for 70.79% longer at 3 V, and for 47.72% longer at 5 V when the thermal pad is applied to the opposite side of the Peltier as the device is cooling.

The second test put the Peltiers in a configuration close to what the devices would be in when in the therapeutic wrap. Fig. 6 shows the flexible Peltier in an incomplete and

Fig. 6. Incomplete (left) and complete (right) arrangement of flexible Peltier in therapeutic wrap materials

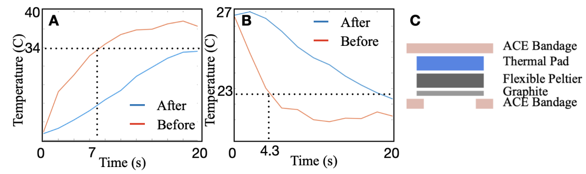

Fig. 7. Heating (A) and cooling (B) mode before and after addition of graphite and ACE bandage and (C) Addition of window in ACE bandage to allow direct heat transfer.

a complete configuration. This test evaluated the impact of selected materials on transferring heat during both hot and cold temperature conditions to the outer surface of the wrap. Each configuration (incomplete/complete) underwent four trials for each mode (heating/cooling), with averages calculated for each set of trials.

The results in Fig. 7 show that it took the complete Peltier configuration 2.8 times longer to reach 34°C when heating compared to the incomplete configuration. It also shows that the complete Peltier configuration took roughly 4.67 times longer to reach 23°C compared to the incomplete configuration. These extended time periods are due to the ACE bandage being an insulating material, preventing the temperatures being produced from the Peltier from being thermally conducted away from the device. From these results, a new configuration is proposed to prevent the accumulation of heat within the ACE bandage and increase the transfer of temperatures being produced by the flexible Peltier to the user. This included cutting out a window in the ACE bandage where the Peltier is, preventing any heat accumulation inside the wrap, and decreasing the amount of time it takes for the temperatures to reach the user. This new configuration is shown in Fig. 7-C.

D. Experimentation of Temperature Hysteresis to Compensate for Heat Sink During Cooling

The Peltier unit experiences overheating, reaching elevated temperatures during the cooling phase within 30 s. Upon turning off the flexible Peltier, the cooling side rapidly warms due to the absence of current flow preventing heat leakage from the heating side. An effective current modulation strategy involves alternating between a high current of 1.0 A and a low current of 0.2 A, with the optimal time ratio being 7 seconds of high current followed by 12 seconds of low current. This approach maintains the Peltier within the temperature range of 18°C to 25°C within 15 seconds, as shown in Fig. 8.

III. Discussion and Conclusion

In this work, we presented a Peltier-integrated therapeutic wrist wrap. Design considerations were discussed to enhance the functionality of the device in providing both cooling and

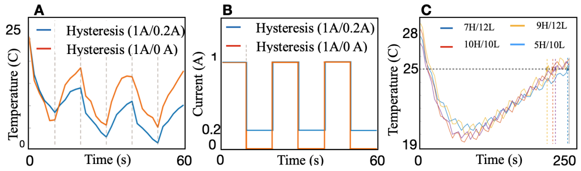

Fig. 8. application of temperature hysteresis in Peltiers, temperature (A), current (B), and ratios of high current (H) and low current (L) time periods, using timer relay (C)

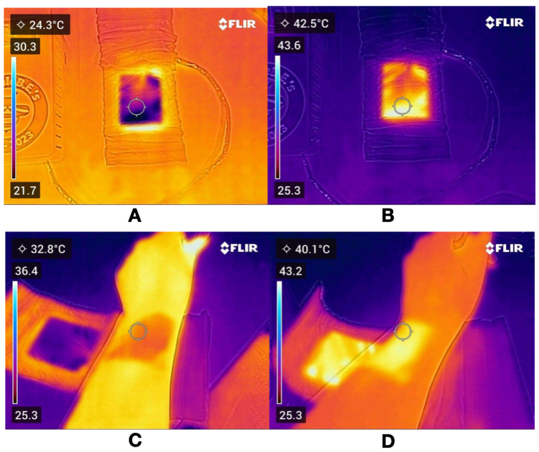

Fig. 9. A:Thermal images of therapeutic wrap in cooling mode, B: heating mode (right), with uneven distribution of temperatures due to thermistor (located at the top of Peltier in these images), C: Thermal images showing cooling, D: and heating function (right) after being applied to the wrist, and the apparent change in skin temperature after 10 seconds.

heating treatments to the users. To observe the temperatures being produced by the flexible Peltier in both the heating and the cooling mode from the exterior of the wrap, a FLIR thermal camera was utilized. First, the wrap was turned on to the cooling mode, then switched to the heating mode. The thermal camera was used to visualize the temperature of nylon material on the exterior of the wrap and show the distribution of temperatures where the double-layer Peltier was placed within the therapeutic wrap. The effect of applying the device to the wrist for 10 seconds is shown Fig. 9. The area where the device was applied on the skin decreased in temperature when exposed to the cooling mode and increased when exposed to the heating mode, after just 10 seconds of application. Building on these findings, future endeavors will concentrate exploring the use of alternate materials such as aluminum foil, ceramic fiber insulation and phase change materials and refining control systems to achieve stable thermal states, increasing the wrap's efficiency, and enhancing the transition dynamics between heating and cooling functionalities for optimal therapeutic outcomes. The research likely improves the integration of flexible Peltier devices in medical and therapeutic applications, with the potential for future embedding in clothing.

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