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Original Article

Design and Development of a Thermoelectric-Based Cold Pack Device

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Abstract *- This study focuses on the design and development of a prototype cold compress device employing thermoelectric cooling technology, based on the Peltier Effect principle, to attain cooling via direct current application. The device is designed to effectively manage acute injuries by ensuring accurate and continuous temperature regulation within 10-13°C, rendering it appropriate for use in medical and sports science environments. The tests aimed to evaluate the performance of four distinct fin sizes paired with four different fan speeds, with the objective of identifying the most efficient heat sink. The components were subsequently merged with a thermoelectric sheet and evaluated on actual surfaces using a cold compress machine and a dummy, with 10 iterations conducted for each situation. The findings indicated that the larger fins and high-velocity fan enabled a more rapid and uniform temperature decrease, allowing the device to reduce surface temperatures by up to 10°C in roughly 16-18 minutes and maintain the desired range for over 14 minutes. The results indicate that the designed device operates with remarkable efficiency and stability, particularly regarding temperature regulation and reproducibility. Consequently, it demonstrates potential for practical application in scenarios necessitating quick cooling and could be evolved into portable healthcare devices in the future.*

Keywords *- Cold pack, Heat dissipation, Medical device, Temperature control, Thermoelectric.*

1. Introduction

Incidents affecting the musculoskeletal system remain a significant concern across all age groups. Such incidents may originate from routine activities, traffic accidents, and participation in sports or exercise [1, 2] all of which pose a risk of acute injury, particularly for those engaged in high levels of physical activity. In individuals such as athletes, laborers, or those experiencing muscle weakness [3], these injuries often affect daily activities and, if not properly managed, may lead to complications or chronic conditions. Therefore, prompt and effective first aid is crucial in alleviating symptoms and reducing the severity of injuries [4]. A widely recognized method for providing acute care is the application of cold compresses, commonly known as cryotherapy [5, 6]. According to the Gate Control Theory, cold treatment inhibits the transmission of pain signals from sensory nerves to the brain by decreasing the activity of pain-related nerve fibers [7]. In addition, cold therapy reduces blood flow, inflammation, and swelling, while slowing cellular metabolism, which is particularly beneficial in the early stages of injury management. Several types of cold compresses exist, including ice packs, gel packs, and vapor coolant sprays [8, 9]. Despite their widespread use, these conventional methods suffer from critical drawbacks: irregular temperature regulation, rapid loss of cooling efficiency [10], poor portability [11], and reliance on external refrigeration [12]. Such limitations restrict their effectiveness in emergency and field settings, where consistent and controllable cooling is essential. This highlights the central problem: existing cold compress devices are unable to provide stable, controllable, and long-lasting cooling for practical medical and sports applications. To overcome these limitations, engineering approaches based on thermoelectric technology have been explored [13, 14]. Devices using the Peltier Effect generate cooling by applying a direct current, creating a temperature gradient across the thermoelectric module [15, 16]. These systems offer distinct advantages such as precise temperature control, sustained cooling duration, and compact form factors suitable for portable applications. However, a clear research gap remains. Previous studies have primarily emphasized general thermoelectric cooling applications, with limited focus on medical cold pack devices. Specifically, few investigations have addressed: (i) maintaining therapeutic temperature ranges (10-13 °C), (ii) systematic evaluation of design parameters such as fin size and fan speed, and (iii) reproducibility of results across multiple trials and under realistic usage scenarios [17]. To date, no comprehensive study has demonstrated a

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thermoelectric cold pack prototype optimized for both clinical and sports science needs. For these reasons, this study aims to design and develop a prototype thermoelectric-based cold compress device that achieves precise and reproducible temperature regulation within the therapeutic range of 10-13 °C. The device is systematically evaluated under varying design configurations and validated on practical surfaces. The objective is to provide a portable and efficient solution that bridges the gap between conventional cold packs and advanced medical-grade cooling devices, thereby contributing to improved first aid, rehabilitation, and sports medicine practices.

2. Materials and Procedures

The effective application of cold compresses is crucial; thus, the design concept aims to maximize their effectiveness. The cold compress machine should effectively dissipate heat and maintain an adequate air flow rate to achieve the desired temperature while also operating within a range of 10-13 degrees Celsius [18]. In the application of cold compresses using a thermoelectric cold compress machine, we prioritize the safety of both users and service recipients, alongside the efficient use of electricity [19].

2.1. Development of a Thermoelectric Cooling System

Cold compresses play a vital role in medical and sports science applications. The design of cold compresses is crucial to guarantee their ease of use, convenience, speed, reusability, and effectiveness. Consequently, a concept has been proposed to develop a cold compress set utilizing thermoelectric technology, as illustrated in Figure 1. Furthermore, an illustration of the equipment is presented in Figure 2.

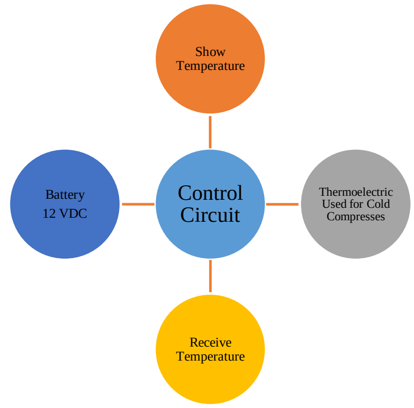

Fig. 1 Design schematic for a thermoelectric cold compress system

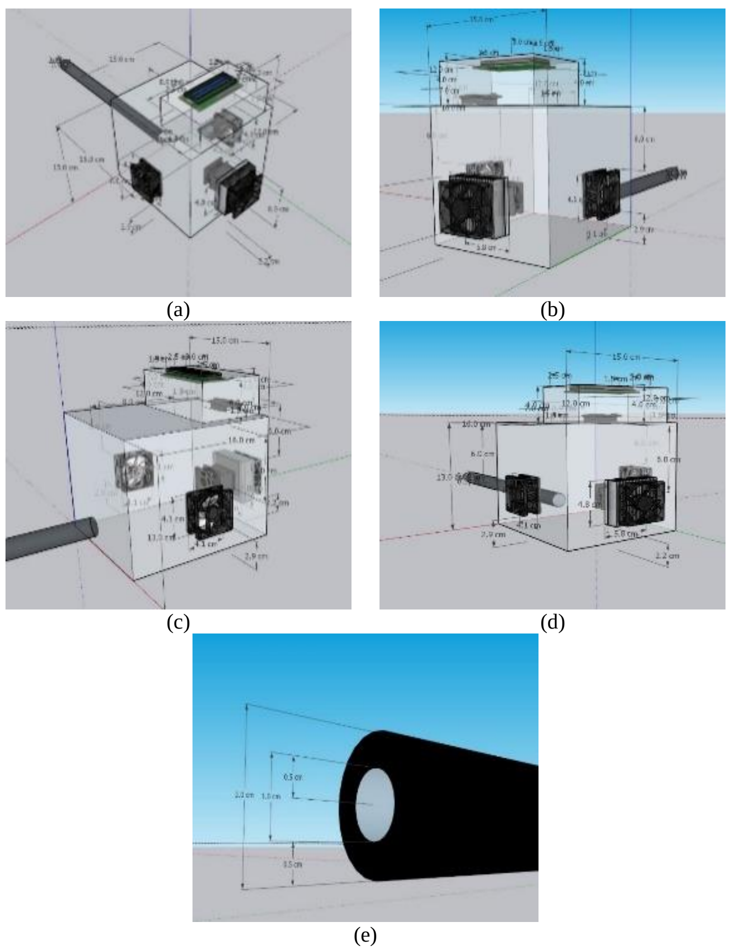

Fig. 2 Shows the three-dimensional structural design of the thermoelectric cold compress device

The specifics are outlined below: (a) Front-left isometric view illustrating the placement of the LCD screen, heat sink, and cooling fan. The front view illustrates the external dimensions of the housing and the positioning of the fan. (c) Rear-Left Isometric View illustrating the positioning of the power supply ports and the cold inlet-outlet configuration. (d) Right-Side View illustrating the configuration of the ventilation fans on either side to enhance heat transfer efficiency. (e) Schematic diagram illustrating the structure of the cold transfer pipe, including both external and internal dimensions.

2.2. Research Methodology

To gather data for evaluating the efficacy of the cold compress device using thermoelectric technology, the researcher executed a systematic test, beginning with a comparison of the effectiveness of four different sizes of cooling fins. The experiment was carried out under controlled conditions, maintaining a constant fan speed to evaluate the heat transfer efficiency of various fin sizes. The optimal fins were subsequently evaluated alongside four distinct fan speeds to ascertain the overall system that delivered the most effective cooling efficiency [20].

After achieving the most efficient cooling system, the researchers integrated it with a thermoelectric sheet and optimized the system to regulate temperatures between 10 and 13 degrees Celsius, which is appropriate for the application of cold compresses. The experiment was performed on the direct contact surface of the cold compress machine for 10 iterations and on the contact surface of the mannequin for an additional 10 iterations to record temperature variations and the operational duration of the device [21]. The data collected from both experimental sets were evaluated to determine the correlation between temperature and cooling time. The objective is to assess the system's efficacy in practical applications, emphasizing the verification of the cold compression device's precision and reliability for medical or post-exercise rehabilitation purposes.

3. Results from the Experiment

Creation of a cooling system designed to enhance thermoelectric efficiency by assessing four different sizes and configurations of cooling fins, with the goal of determining the fin that provides the most efficient heat dissipation. Configure a set of ventilation fans and record the outcomes in Table 1. Assemble the cooling system and determine the differential values of four cooling fin sizes while maintaining a consistent Revolutions Per Minute (RPM) for the cooling fan. Document the findings in Table 2. Choose a cooling motor by designing and selecting a motor that offers four distinct speeds: 2000 rpm at 0.1 A, 3000 rpm at 0.15 A, 4500 rpm at 0.2 A, and 6000 rpm at 0.3 A. Each motor undergoes testing to identify the motor with optimal heat dissipation capabilities, which is then paired with the most effective cooling fins. The results are documented in Table 3.

Table 1. Variations in cooling fins

Time (min)	Fin 1 40x40x11 cm.	Fin 2 60x60x45 cm.	Fin 3 90x95x34 cm.	Fin 4 120x130x50 cm.
0	34.41	34.35	34.38	34.42
0.5	32.90	32.73	32.78	32.65
1	31.76	31.35	31.31	31.18
1.5	30.81	30.64	30.22	29.95
2	30.10	29.84	29.31	28.76
2.5	29.55	29.31	28.58	27.87
3	29.10	28.92	28.05	27.21
3.5	28.79	28.54	27.68	26.75
4	28.53	28.24	27.36	26.48
4.5	28.35	28.00	27.13	26.26
5	28.21	27.85	27.02	26.15

Table 2. Variations in cooling fins at a motor speed of 6000 RPM

Time (min)	Fin 1 40x40x11 cm.	Fin 2 60x60x45 cm.	Fin 3 90x95x34 cm.	Fin 4 120x130x50 cm.
0	34.33	34.29	34.41	34.44
0.5	32.35	32.45	32.55	32.65
1	30.69	30.72	30.88	31.02
1.5	29.17	29.21	29.35	29.44
2	28.12	28.01	28.06	27.95
2.5	27.31	27.05	27.05	26.56
3	26.65	26.32	26.14	25.44
3.5	26.15	25.75	25.33	24.51
4	25.75	25.31	24.58	23.76
4.5	25.42	25.01	24.12	23.31
5	25.27	24.82	23.95	23.08

Table 3. Variations in the fine ventilation fan motors with dimensions of 120x130x50 cm

Time (min)	2000 rpm (0.1 A)	3000 rpm (0.15 A)	4500 rpm (0.2 A)	6000 rpm (0.3 A)
0.0	34.41 °C	34.40 °C	34.39 °C	34.44 °C
0.5	32.56 °C	32.25 °C	31.75 °C	32.65 °C
1.0	31.02 °C	30.42 °C	29.65 °C	31.02 °C
1.5	29.66 °C	28.87 °C	27.98 °C	29.44 °C
2.0	28.41 °C	27.63 °C	26.71 °C	27.95 °C
2.5	27.36 °C	26.60 °C	25.65 °C	26.57 °C
3.0	26.35 °C	25.72 °C	24.66 °C	25.44 °C
3.5	25.61 °C	24.85 °C	23.86 °C	24.51 °C
4.0	25.54 °C	24.41 °C	23.63 °C	23.61 °C
4.5	25.22 °C	24.21 °C	23.42 °C	23.28 °C
5.0	25.00 °C	24.21 °C	23.42 °C	23.08 °C

The correlation between temperature and the duration of the cold compress, as well as the skin texture of the doll, was determined through an average of 10 trials, with the findings documented in Table 4.

Table 4. Correlation between the average values of the cold compress surface and the dummy surface

Time (min)	The texture of the cold compress (°C)	The texture of the doll (°C)
0	34	32
2	23	24
4	17	20
6	14	16
8	13	14
10	11	13
12	10	11
14	10	11
16	10	10
18	10	10
20	10	10

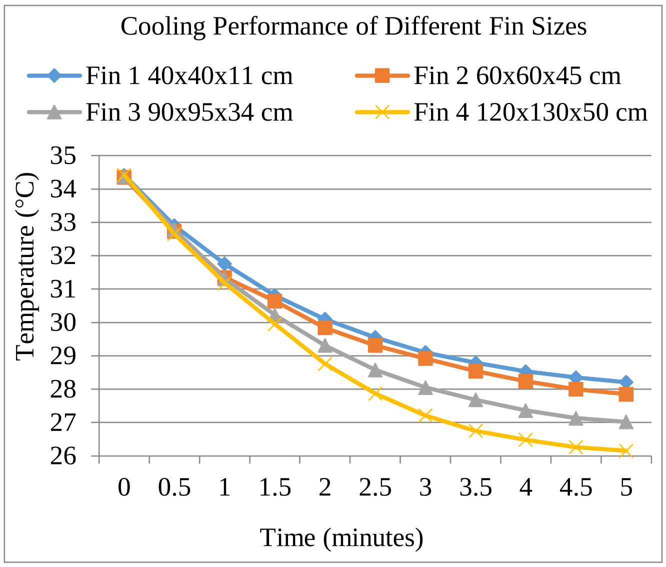

Fig. 3 Results of finding the difference values of 4 cooling fin sizes

Figure 3 shows the variation in cooling performance based on fin size. It can be concluded that larger fins possess increased surface area, facilitating improved heat transfer, which leads to enhanced performance and reduced system temperatures. The observed temperature variation between Fin 1 and 4 is notable, particularly after 2.5 minutes, suggesting that selecting the appropriate fin size can greatly enhance temperature regulation. The variations in fin sizes shown in the graph indicate the importance of selecting the appropriate fin size for the cooling application. Figure 4 shows the experimental results obtained at a constant fan speed of 6000 RPM, facilitating a focused comparison of the outcomes specifically related to the "effect of fin size." Maintaining a consistent fan speed eliminates the variable of airflow, thereby isolating the impact of fin size for analysis. The findings demonstrate that increased fin sizes lead to a more rapid and significant decrease in temperature, particularly after a duration of 2.5 minutes. The final temperature difference demonstrates that Fin 4 exhibits the highest heat transfer potential, followed by Fin 3, Fin 2, and Fin 1 in that order.

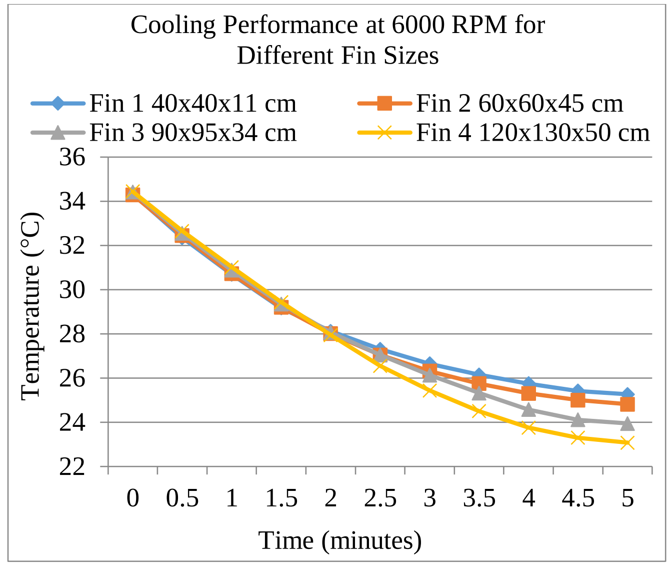

Fig. 4 The results of finding the difference values of 4 sizes of cooling fins, based on the same rpm (Revolutions per minute) values of the cooling fans

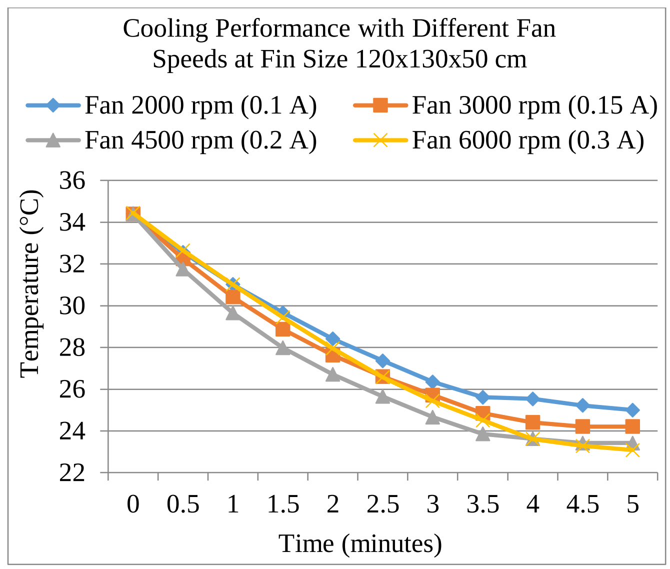

Fig. 5 The results of finding the motor size at different rpm speeds of 4 sizes of ventilation fans with Fin size 120x130x50 cm

Figure 5 assesses the impact of fan speed (RPM) in conjunction with motor size or rating (in A) on cooling efficiency while maintaining a consistent fin size to regulate the surface area variable. The findings demonstrate that with an increase in fan speed, the system temperature declines more swiftly and reaches a lower value as a result of enhanced airflow.

The present consumption rises with speed, showing a balance between cooling efficiency and power consumption. Achieving a balance between efficiency and power consumption requires consideration of the fact that a fan speed of 4500 rpm can deliver performance comparable to 6000 rpm, while consuming less current.

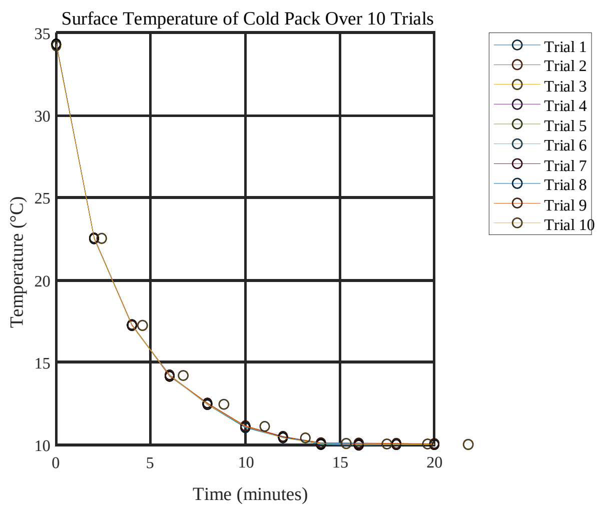

Fig. 6 The results of the actual experiment with the surface of the cold compress machine were 10 times to find the temperature of 10 degrees Celsius that occurs on the surface of the cold compress machine

Figure 6 shows that the cold compress is capable of lowering the surface temperature by 10°C in roughly 17 minutes, maintaining consistent operating conditions for each cycle. Ten trials were conducted to assess reliability, a process that guarantees the precision and accuracy of the system. The variation between cycles is minimal, demonstrating that the device maintains stability throughout repeated cooling cycles. The asymptotic behavior signifies the dynamic limit of the system at which the cooling capacity approaches its maximum threshold.

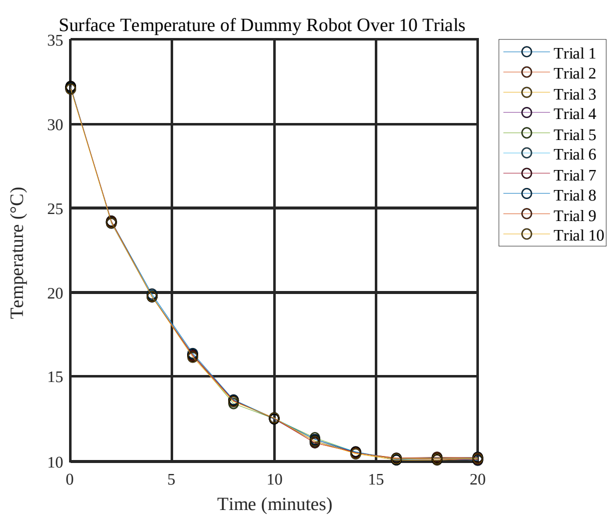

Fig. 7 The results of the actual experiment with the surface of the robot, 10 times, to find the temperature of 10 degrees Celsius that occurs on the surface of the robot

Figure 7 shows a ten-repeated experiment conducted on a dummy surface, offering significant insights that the cooling system can consistently and reliably lower the dummy surface temperature without variability between cycles. The temperature declines swiftly at the outset, indicating the system's effective initial heat transfer rate. As it nears 10°C, the system attains a steady state, a characteristic behavior observed in dynamic cooling processes. The average duration required to achieve 10°C is approximately 17–18 minutes, which aligns with the findings obtained using compressed plates (Figure 6).

Figure 8 shows that the cold compress effectively reduces temperature at a significantly faster rate than the dummy surface during the initial 0–10 minutes, a critical timeframe for practical applications in the treatment or management of acute injuries. In the meantime, the dummy surface, designed to replicate actual skin conditions, exhibits a slower cooling rate but is capable of achieving a temperature of 10°C in roughly 17 to 18 minutes. The average outcomes from these 10 trials show the system's efficiency, stability, and accuracy in regulating temperature on both the device and dummy surfaces.

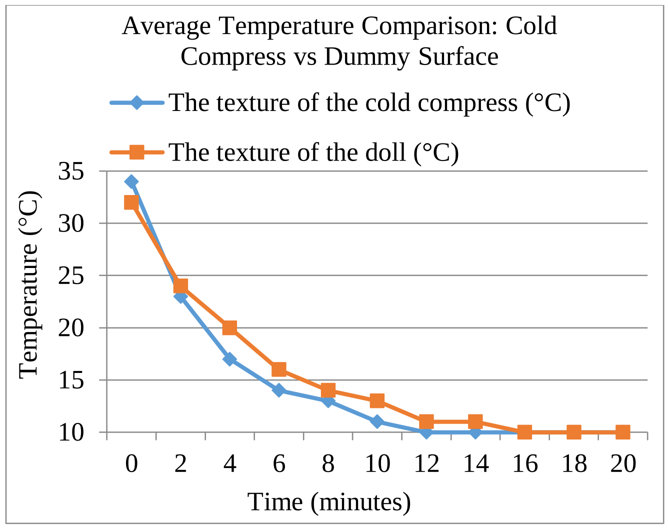

Fig. 8 The results of the temperature and time relationship of the cold compress surface and the dummy surface from the average of 10 times

4. Conclusion

The analysis of the design and construction of cold compress devices using thermoelectric technology revealed that the physical components of the cooling system significantly influence the efficiency of temperature reduction. Cooling fins with extended lengths offer superior heat transfer efficiency compared to shorter fins, regardless of whether the fan speed remains constant or varies with different rpm values. Research indicates that fans operating at higher RPMs deliver enhanced cooling efficiency.

The experiment involving the cold compress machine and the surface of the dummy, conducted ten times, revealed consistent temperature measurements throughout. The temperature can be sustained within the range of 10–13 degrees Celsius for approximately 14 minutes, which is deemed suitable for cold compress applications and for clinical or first aid purposes. The temperature during the 16–20 minute period exhibited minor fluctuations from the ambient temperature; however, it remained stable and did not impact the quality of the cold compresses.

It is advisable to install the device in a manner that ensures a snug fit against the user's skin to minimize cooling loss. Using thermal conductive silicone as a connector between the thermoelectric sheet and the heat sink is essential for enhancing cooling efficiency and improving durability.

Additionally, sealing any openings or holes in the device's structure will contribute to minimizing temperature loss and effectively prolonging its lifespan.In future applications, the device has the potential to be advanced into a prototype for a compact hot and cold-water dispenser or utilized in a portable temperature control system for patients, athletes, or mobile first aid units. The device offers customization in both size and form to accommodate a range of scenarios.

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