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Research Paper

An automatic and portable prosthetic cooling device with high cooling capacity based on phase change

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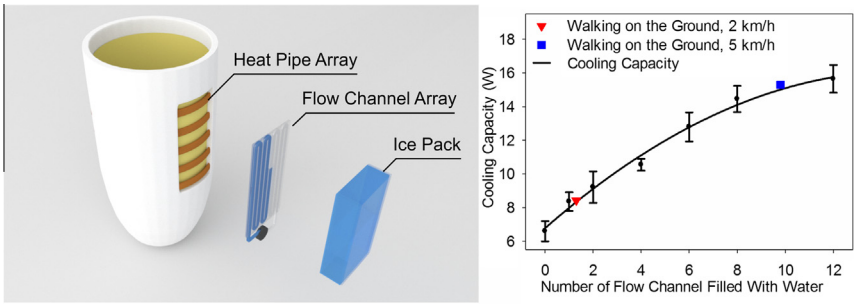
HIGHLIGHTS

- An automatic and portable cooling device for lower-limb prosthesis is demonstrated.
- Adjustable thermal resistance using fluid pipes is invented and demonstrated.
- High cooling capacity has been achieved without using a fan.
- The device maintains a constant skin temperature for a thermal load up to 15.6 W.
- The device can remove excess heat for all patient activity patterns.

GRAPHICAL ABSTRACT



Prosthesis cooling device Cooling capacity of the device

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ABSTRACT

Lower limb prosthesis wearers usually suffer from excessive heat and resulted perspiration within a prosthetic socket. We present a novel cooling device that can remove excessive heat and maintain a desired skin temperature in a lower-limb prosthesis. To remove excessive metabolic heat, the cooling device used heat pipes to collect heat generated from the residual limb and dissipate heat to an external ice pack. More importantly by using a novel flow channel array, the system thermal resistance was adjustable, and a cooling capacity ranging from 6.6 W to 15.6 W was achieved to cover various wearer activities. We demonstrated the device's capability of removing excessive heat under two simulated walking activity patters (at 2 km/h and 5 km/h); and the skin temperature was maintained constant at 31.4 °C ± 0.2 °C by using corresponding cooling conditions. Finally, we demonstrated that by using an automatic control scheme the system can maintain a constant, desired skin temperature under varying thermal loads. With its compact size, high cooling capacity and flexibility of operation, this device is promising for reducing skin maceration and increasing the quality of life for prosthesis users.

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1. Introduction

Excessive heat within the prosthetic socket can significantly reduce the quality of life of an amputee patient and may even lead to dermatologic problems [1–4]. Currently, liner and socket with poor thermal conductivity are often used in the prosthetic [5,6]. Inside the socket, the residual limb is thermally insulated and the skin temperature is elevated even if the wearer is at sedentary activity, resulting in excessive sweating and concomitant skin maceration. In addition, heat generation (thermal load) within the residual limb can increase rapidly when a wearer is switching to vigorous activities, and significant amount of heat will be accumulated [7–9]. Therefore it is utmost important to dissipate the excessive heat from the prosthetic socket and maintain a

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comfortable skin temperature, when the amputee patient performs various activities. Ideally a prosthesis cooling device should have (1) high cooling power to remove excessive heat from the residual limb, (2) ability to maintain a constant skin temperature under varying activities, (3) automatic operation and easy maintenance.

To date various systems have been developed for personal thermoregulations using ambient environment as the cold source. Among them, air cooling systems can remove metabolic heat based on forced air convection [10–12]. Within the air cooling systems, air was forced to pass through channels in contact with skin and transfer heat from the skin surface. Because of the small temperature difference between the skin and forced airflow, the heat transfer flux and cooling power are typically low [13]. Recently efforts have been made utilizing heat pipes to circumvent the large thermal resistance of the plastic socket [14]. Because the device was based on air cooling, the device had a low cooling power (up to 7 W). Thermoelectric cooling device (TEC) utilizing Peltier effect [15] is another type of device that transfers heat to the ambient environment. Cooling power of TEC devices can be controlled by controlling the input electrical power [16–18]. TEC devices are compact in size and have no moving parts. However, because of the low coefficient of performance (COP) [19], TEC cooling devices typically have low cooling capacity and large power consumption.

To further increase the cooling power, cold sources with low temperature (~0 °C) have been widely adopted and were integrated into different cooling systems. One type is the liquid cooling systems using ice or dry ice as the cold source, and water as heat transfer medium [20,21], which have been integrated into thermal regulation suits for high temperature and hazardous environment [22–26], and deep-ocean and space operation missions [13,27]. Compared with air cooling methods, liquid cooling methods offer higher cooling capacity because of higher convective heat transfer coefficient and the use of a much lower temperature source (e.g., ice). However, liquid flow rate is often controlled to change the cooling power, which requires not only complex tubing system but also high power consumption to circulate the flow. To circumvent the complex tubing system, phase change materials (PCM) were directly integrated into garments to absorb excess metabolic heat [28,29]. However it is difficult to regulate the heat exchange rate for various activities because the system has a constant thermal resistance.

To address the above requirements, here we report a new cooling device that can maintain a constant comfort temperature on the simulated residual limb surface. This cooling device can efficiently remove heat from 7 W to 16 W, by adjusting a novel thermal resistor made of a flow channel array. We also demonstrated that under varying activity patterns, the surface temperature of a residual limb can be maintained at 31.4 °C by using an automatic temperature control scheme.

2. Design concept and experiment setup

The design concept of the lower-limb prosthetic cooling device is shown in Fig. 1(a). It consists of three major parts: (1) a heat pipe array built in the prosthetic socket and placed in contact with the liner surface, (2) a flow channel array placed between the heat pipe array and the ice pack, and (3) an ice pack serving as the cold source to absorb heat by phase change. To analyze the heat transfer process between a residual limb and the ice pack, the thermal resistance model of the prosthesis with the cooling device is shown in Fig. 1(b). The heat generated from a residual limb (q) is transferred through the liner (R_l), socket (R_s), heat pipe array (R_{hp}) and flow channel array (R_f), and finally dissipated to the ice pack. Without using the cooling device, the thermal resistance of the prosthesis consists of the liner (R_l) and the socket (R_s). Compared with a

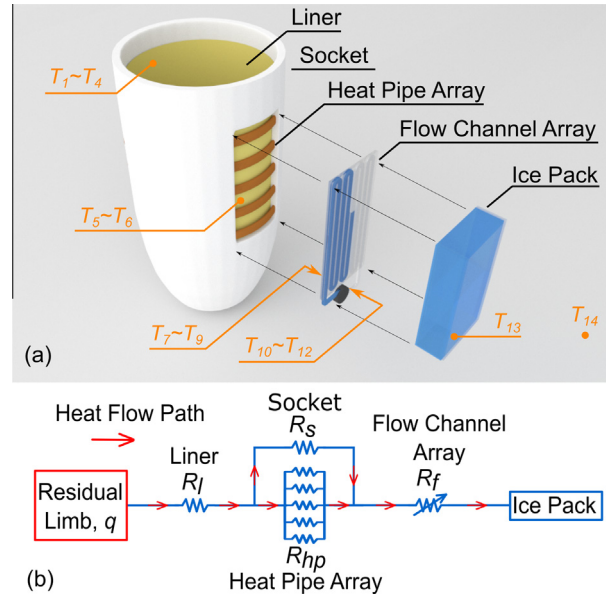

Fig. 1. (a) Schematic of the lower-limb prosthetic cooling device. (b) The thermal resistance model of the heat transfer from a residual limb to an ice pack.

conventional prosthetic socket that transfer heat through poor conductivity materials (R_s), this cooling system utilizes a heat pipe array to bypass the original socket thermal resistance (R_s) with a much lower thermal resistance (R_{hp}), and to concentrate heat to a small cooling region outside of the socket where miniaturized cooling device is attached. The flow channel array enables an adjustable thermal resistance which can be controlled by changing the volume of water filled into the channels; cooling capacity of the device can thus be tuned to match variable thermal loads generated from various activities. Additionally, compared with conventional prosthetic that dissipating heat to ambient (e.g. from 31 °C to 23 °C) via air cooling, we integrated an ice pack into the system that increased the temperature difference (e.g. from 31 °C to 0 °C) by three times.

To simulate a residual limb which has heat conduction, storage and generation functions according to the bio-heat model, we used a bucket filled with water to simulate a residual limb. The simulated residual limb was designed according to the one dimensional bio-heat model, as shown in Eq. (1)

$$\frac{d^2T}{dx^2} + \frac{\dot{q}_m + \dot{q}_p}{k} = 0 \tag{1}$$

where $\dot{q}_m$ and $\dot{q}_p$ are the metabolic heat source term and perfusion heat source term, k is the thermal conductivity of the tissue, x is the radiant distance from residual limb center to the outer skin. According to our previous study [14] and studies by other researchers [30,31], the perfusion heat generation for a residual limb was calculated to be 0.56 W and remains constant when tissue temperature is below the 42.5 °C. Comparing with the metabolic heat source (8.4 W and 15.3 W when walking on level ground at 2 km/h and at 5 km/h), the perfusion heat source is low and remains constant under different activities. Therefore, we neglected the perfusion heat generation term and set the testing thermal loads according to metabolic heat generate rate only. Within the bucket, an immersion heater (114.8 Ω) was used to generate thermal loads to mimic the heat generation from various wearer activities. The stainless steel bucket is 160.0 mm in length and 135.0 mm in diameter, which are typical dimensions of an upper residual limb. Water was filled into the bucket to mimic the heat conduction function of a prosthetic leg because water has similar thermal conductivity

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