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Size and Shape Design Requirements for Lower Limb Prosthetic Cooling System: A Literature Review

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ABSTRACT: Amputees suffer from sores and injuries caused by friction and pressure, which causes the amputated part attached to the prosthesis to overheat. Many researchers worked on analyzing the temperature of the contact area and designing a cooling and ventilation system for it in different ways. In the same time the consideration of shape, size and weight is very important for prosthetic design. The present work reviews previous researches related to prosthetic limb cooling designs for the purpose of evaluation the ability of these designs to optimize the size, shape and weight requirements for better improvements. It has been concluded that an efficient design could be realized by using of phase change materials as a heat sink. However these studies required complementary work to fix the other parameters for optimization purpose among them. The present work will be complemented by additional work that clarifies the detailed design of proper cooling system for lower limb amputees using phase-changing materials with a sustainable capacity using walking energy. Such design will take under consideration the limitations of size and shape, and therefore constructal theory will be used in the future design.

KEYWORDS: Socket, cooling, prostheses, PCM, heat transfer, optimization.

I. INTRODUCTION

In recent decades, the condition of amputation has increased as a result of wars, traffic accidents and work, as well as amputations as a result of chronic diseases [1] [2]. To compensate for the missing part, prosthetic limbs are used to perform functions almost normally and to obtain the aesthetic of the whole body. The use of the prosthetic requires direct contact between it and the amputated part to ensure rigidity and perform functions satisfactorily. This leads to high temperatures due to global warming and friction, which causes ulcers and discomfort. For this reason, designers are focused on alternatives to mitigate such adverse drawbacks by allowing for minor ventilation and adding a cooling system to the prosthetic seam area [3].The addition of cooling systems must take into account size, shape and weight in order to adapt to the functional performance of the considered party.The prosthetic performs the function of the natural limb of carrying loads and contributing to motivated activity such as walking for the lower limbs. The lower limb prosthetic usually consists of the following parts: the foot that is usually made of flexible materials for the purpose of providing the dorsiflexion angle of astronomy and sometimes designed with a flexibility suitable for some sports. The pylon is the part connected to the foot and is usually a simplified part in the form of a column to support the body. The knee joint in the above the knee prosthetic, and finally the socket, which is the supporting part of the amputation and directly contact to it.The lines are now made primarily from the outer fabric layer and the inner elastomer layer, which are usually either silicon, thermal plastics, or polyurethane [4] [5]. Figure (1) shows the main parts of above-knee amputation.Amputees using the prosthetic limb have difficulty equalizing the temperature of the contact area with the limb due to the thermal properties of the socket, which are usually low in thermal conductivity, as well as a decrease in the surface area of heat transmission.In hot and/or humid areas, the use of prosthetic limbs can lead to excessive sweating and thermal discomfort [6] [7]. Such syndrome affects the environment between the lining and the skin is an ideal set of residual limb skin problems including contact dermatitis as shown

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in Figure 2. Several studies have been conducted in the field of designing cooling and ventilation systems for the prosthesis. In Iraq, where the air temperature is almost high along the whole year, the use of orthopedic limb systems supported by cooling systems is considered an important matter to gain thermal comfort while doing business for amputees, whose numbers have increased due to wars, explosions and mine. Equipping the prosthesis with a cooling system that performs perfectly must take into account the limitations of shape, size and weight to ensure kinetic balance and load distribution in addition to the aesthetic aspect. Previous researches have been reviewed from the point of meeting these requirements.

Figure 1. The various parts of a lower-limb prosthesis. [8]

Figure 2 Examples of skin problems present on the amputation stump of participants

II. DESIGN REQUIREMENTS

The design of prosthetic cooling system is based on the direct cooling from socket to tissue. The thermal model is based on the Pennes' biological heat transfer equation, [9].

$$\rho c \frac{\partial T}{\partial t} = \nabla k \nabla T + \omega_b \rho_b c_b (T_b - T) + q_m \ldots.. 1$$

Where ρ, c, k and T are tissue density (kg/m^3), specific heat (J/kg.K), thermal conductivity (W/m K), and temperature (K). The subscript b refers to properties of blood. ω represent to perfusion rate (s^{-1}). q_m represent the heat flow of metabolic (W/m /s).

Jeffrey et.al. [9] predicted skin temperatures near to the prosthetic socket using finite element method. This study and similar ones enabled researchers to design the cooling systems needed by the prosthetics for amputees. Kathleen [10] designed a sensing control instrument using digital thermometers and measuring blood flow using the Doppler phenomenon. This study was used to know the tissue response to cooling related to the prosthetic limb.

Christina et.al. [11] measured and collected the thermal properties of materials used in extrusion of prosthetic limbs and supports. He expressed the importance of this technique in transferring heat from tissues during various activities. The mechanical properties are arranged as in Table 1.

Table 1. Thermal conductivities of prosthetic materials [11]

Material	Thickness mm	Thermal connectivity W/m K	SD
Elastomers			
A	3.9	0.145	0.012
B	5.36	0.155	0.002
C	4.23	0.148	0.011
Fabrics			
D	2.19	0.056	0.004
E	2.04	0.046	0.003
F	1.4	0.063	0.005
G	1.35	0.063	0.003
H	0.72	0.045	0.002
I	1.28	0.074	0.002
J	0.89	0.061	0.006
K	1.16	0.054	0.003
L	1.05	0.047	0.002
Liners			
M	3.01	0.122	0.002
N	3.95	0.116	0.003
O	3.1	0.117	0.003
P	5.92	0.143	0.006
Q	6.32	0.13	0.003
Socket			
R	4.63	0.141	0.002
S	4.42	0.133	0.003
T	5.22	0.153	0.001
U	4.87	0.189	0.004
V	4.83	0.186	0.006
W	4.45	0.146	0.003

Glennet.al. [12] studied the effect of different activities on the amputee’s skin temperature. The work was done by nine lower amputees. 16 thermometers were distributed in the amputee area (contact and near contact to the socket). Different walking speed according to patients’ activities were tested and for 15 to 30 minutes periods. They were concluded that the activity causes a rapid increase in skin temperature ranged from 0.8^{o}C to 3.1^{o}C. The increasing on temperature and heat and perspiration discomfort inside prostheses represented the keys to design prosthetic cooling system [13].

III. DESIGN MODELS

There are different designs for sockets with cooling. One of them is that by Webber et.al. [14], the design is based on manufacturing two halves for socket as shown in figure 3. 3D printer was used to manufacture two flanged socket halves with internal 48mm diameter helical channel for cooling water circulation. As shown that the flanged socket does not achieve the optimal size and shape required. This affects the comfort of the amputee and impairs various functions.

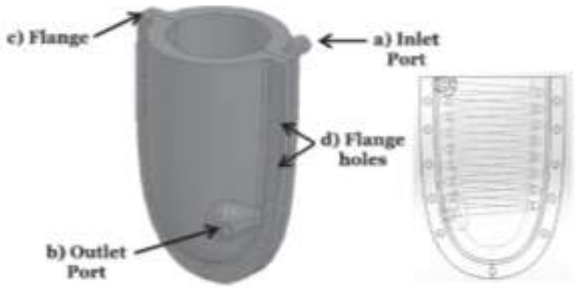

Figure 3 Webber's socket

Garrett Dowd[15] designed a socket prototype with rectangular cross section cooling fluid channel (10.2x4 mm) and heat sink with fan as shown in figure 4.

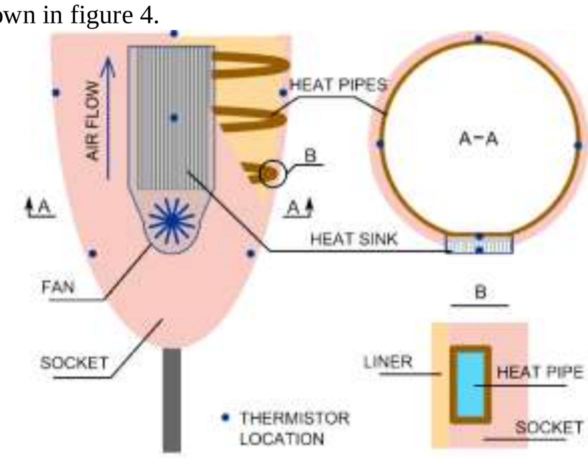

Figure 4 Garrett's socket.

The socket with high thickness and built-in fan also give Restriction in shape and impact on the appearance and function of the prosthesis. Same device was published by Yu Han, Fan Liu, Garrett Dowd and Jiang Zhe [16].

Matthew et al., [17] tested smart Temp liner for thermally perfoance compared with conventional liner. They found that its using developed liner temperature decreases after 25 minutes training of amputee comparing with conventional liner. The Smart Temp limits the temperature increase by 71% and decreasing in perspiration by about 97%. The effect of liner materials and design was studies by Schreven [18],Cagle et al [19], Cyrus et al., [20] and Williams et.al. [21]

Yu Han et al., [22] designed cooling device using phase change material. The PCM used is water and the design is as shown in figure 5. Figure 5-c show the arrangement of the socket. It was shown that the shape is not considered in the design.

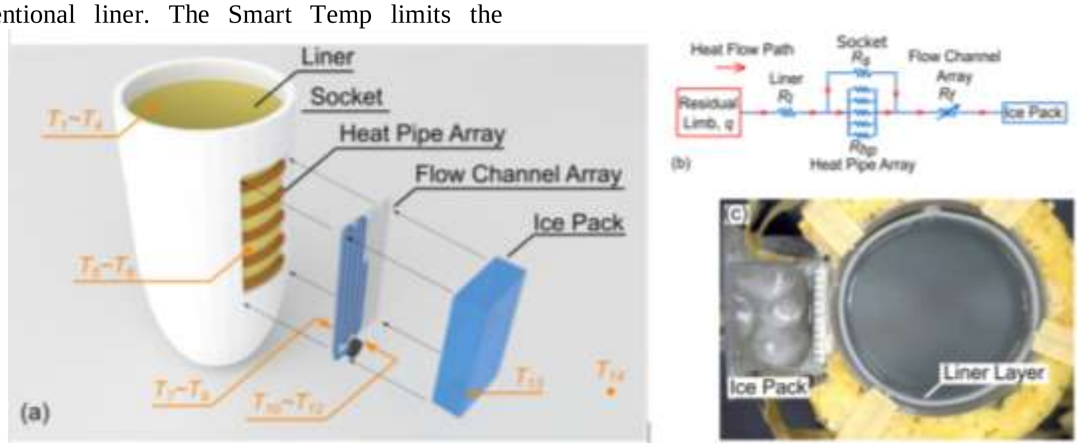

Figure 5. Han's socket

Filip et al. [23], manufactured socket with ventilation holes as shown in figure 6. The holes are useful for medium temperature climate and it is not qualified in hot climate like Iraq.Ghoseiri et al. [24], studied the temperature distribution in the prosthetic- tissue contact through different operations. They found significant difference in skin temperature.

Oldfreya et al. [25], designed and manufactured liner and socket using 3D printing technique. The cooling device is based on the PCM heat sink as shown in figure 7.
The design socket by using 3D scanning. The heat exchanger between air and PCM did not satisfy the shape and volume. Also the distribution of cooling channel is selected without optimization.

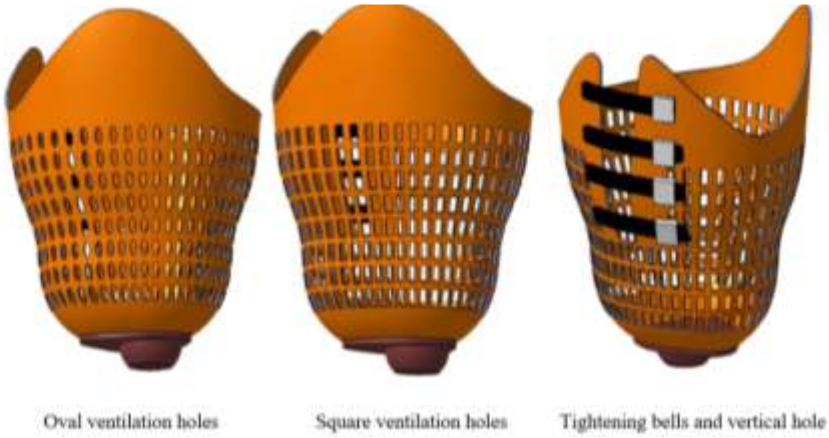

Figure 6 Filip's Socket

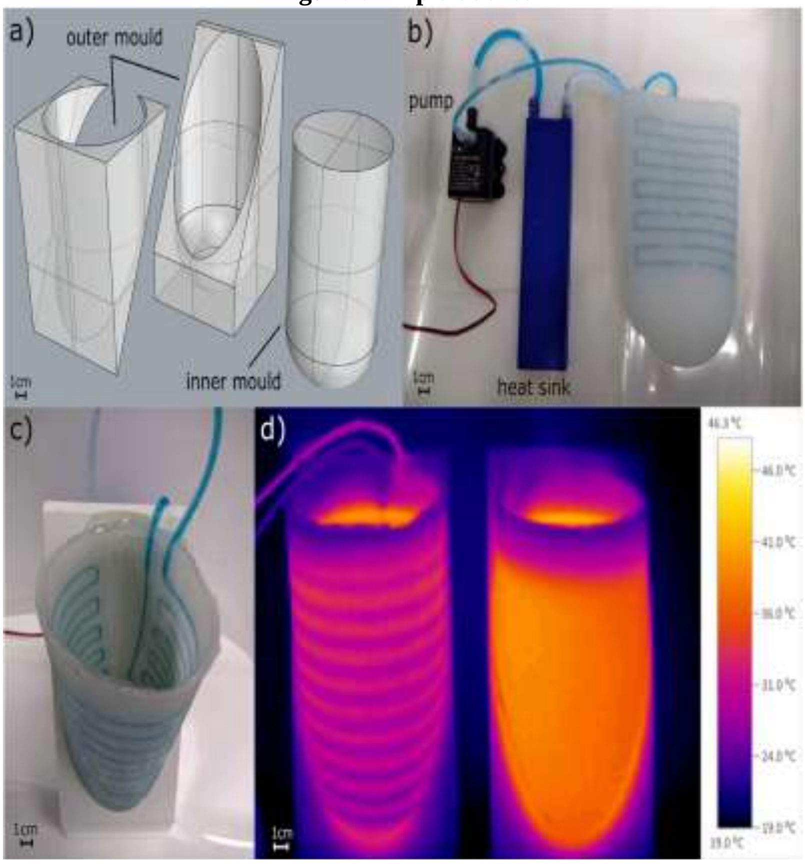

Figure 7 Old Freya's Liner

IV. CONCLUSIONS AND FUTURE WORK:

The addition of cooling systems to the lower prosthetics in hotclimate countries is considered one of the important things to increase the feeling of comfort and to perform the various functions better. Researchers have been designing different cooling systems. An efficient design is the use of phase change materials as a heat sink. while in many studies did not take into account the determinants of size and shape necessary for comfort and easy completion of work. Therefore, our future work will be to design and manufacture a cooling system for lower limb amputees using phase-changing materials with a sustainable capacity using walking energy. Provided that the design takes into account the limitations of size and shape, and therefore constructal theory will be used in the future design.

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