Original Article

Designing, Manufacturing, and Evaluating the Performance of Active Liquid Cooling Vest in Hot Laboratory Conditions

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Abstract

Aim: The present study aims to design, manufacture, and evaluate the performance of an active liquid cooling vest (ALCV) to control the heat strain in hot laboratory conditions. **Materials and Methods:** An ALCV was designed with a cold liquid circulation system in tubes embedded inside the vest. A performance of ALCV in the hot laboratory conditions with an average temperature of 38.5°C and relative humidity of 40% was done with ALCV and none-ALCV (NALCV). Parameters such as heart rate, oral temperature (OT), thermal sensation (TS), perceived exertion (PE), and chest temperature (CT), forehead temperature (FT), and scapula temperature (ST) were measured. Paired *t*-test was used to compare the average of the data. **Results:** The results illustrated that the difference between the average temperature of the ST and CT with ALCV and NALCV, it was 2°C ± 0.5°C. There was a statistically significant difference between the average PE and TS in two testing conditions ($P < 0.05$). Paired *t*-test showed that there is no significant difference between the average FT and OT in the two testing conditions ($P > 0.05$). **Conclusion:** Due to the positive effects of the designed ALCV in reducing skin temperature, heat sensation, and PE, this cooling vest can be used as a useful and cost-effective solution to reduce the level of heat strain in hot environments.

Keywords: Active liquid cooling vest, heat strain, hot conditions

Introduction

Individuals with jobs that involve outdoor activities, such as military, agriculture, building construction, and road construction are exposed to heat stress during the hot seasons, especially in the tropical areas due to outdoor activities and direct exposure to sunlight.[1,2] In addition, heat production by body metabolisms should also be considered as a factor that leads to this difficulty.[3] Furthermore, in multiple sclerosis (MS) patients, increase the ambient heat can aggravate nervous attacks and cause complications such as weakness and blurred vision, movement limitation, speech disorders, etc., so these people have transportation restrictions in hot seasons or have employment ban in a warm working environment.[4]

In some workplaces, it is not possible to install cooling systems, due to several reasons such as limited space, outdoor environment, hot production processes and also in many occupations such as fire fighters, bakers, and microbial laboratories, people have to wear insulated, extremely warm, and heavy protective clothes to prevent physical, chemical, and environmental damage.[5] Therefore, personal cooling equipment can be the best solution to eliminate and reduce heat stress.[6]

Cooling vests can be a best solution to reduce heat stress in the hot condition. Different types of cooling vests include phase change material (PCM) vests, active liquid cooling vest (ALCV), and compressed air cooling vests, and evaporative cooling vests.[7] Whether which type of cooling system is used, depends on many factors such as the weight of the cooling vest, preparation process, cooling capacity, compatibility, environmental conditions, and durability and portability.[8]

Compressed air cooling vests are mainly used for activities that require less movement of the worker, PCMs vest make it

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difficult for the user to bend and straighten body, Moreover, PCM packages need for a freezer to freeze the packages, it imposes restrictions on user's usage.[9,10]

In direct contradiction to PCM vests, ALCV give users more mobility in moving, bending, and straightening body. In addition, the users experience more thermal comfort. Furthermore, compared to the compressed air cooling vest, it can be concluded that the cooling performance of the ALCV is much stronger than the compressed air system due to the heat transfer power of water over the air.[11]

ALCVs that are available in the foreign market cannot regulate the coolant flow rate, so the amount of cooling capacity cannot be controlled by the user. In addition, ergonomic skills are not considered in the backpack design and the user has to move a large and heavy backpack.[11] Furthermore, the commercial price of the ALCV is 800 ± 100 $, which is not affordable for the domestic use. Therefore, the purpose of this study was to design and manufacture a prototype of an ALCV that provides several aspects of thermal comfort, safety, and ergonomics. Due to the price issue of foreign brands ALCV, an attempt was made to design and manufacture a domestic ALCV, using the facilities available in the local market and to establish a basis to produce it at a lower price.

Materials and Methods

The present study was performed in two phases including designing and manufacturing and evaluation of ALCV.

Phase 1: Design and manufacture

Sewing of the vest

The outer layer of the vest was made of 100% linen fabric and weighed 250 g per square meter. This fabric has the most permeability among the samples available in the available, in addition, it is very light and cool. The inner layer of the vest was made of a Lace fabric with a 2 mm size to mitigate the installation of silicone tubes.

Tubes structure

All flexible tubes available in the market (6 samples including PVC, silicone, polycarbonate, polyethylene, latex, and PTFE) were collected. PTFE and polycarbonate tubes were excluded from the study due to insufficient flexibility. The amount of heat transfer of each tube was investigated, and finally, the silicone tube was selected due to having the highest heat transfer coefficient. Then, available samples of a silicone tube with different thicknesses (mantle) and internal diameter were gathered. Among these samples, the silicone tube which had 4 mm internal diameter and 1 mm thickness was selected as the best option regarding the folding status of the tube and the amount of heat transfer. The tubes were sewn in four separate sections on the inner layer [Figure 1].

Pump selection

Due to the necessity of maintaining the output flow at a certain level, at least 1.1 L/min, 5 aquarium pumps and fountains with different pumping heights were prepared, then after laboratory tests have been performed, finally the aquarium pump which reported to have a head height of 6 m was selected as the most suitable option to provide the required output flow through the path of the tube. However, due to the required voltage of 220 volts in municipal electricity and the detection of the risk of electrical leakage, it was eliminated from further research. The focus then shifted to the 12V pumps, including gas pumps, water jet pumps, car windshield wiper pumps, diesel pumps, and finally, the L90 car's windshield wiper pump was opted as the best option due to its safe 12V voltage, ability to operate with the least heat production, the capability to operate continuously for up to 4 h, the least noise production, the least vibration, the right size, the right placement of input and output and requiring a low volume battery.

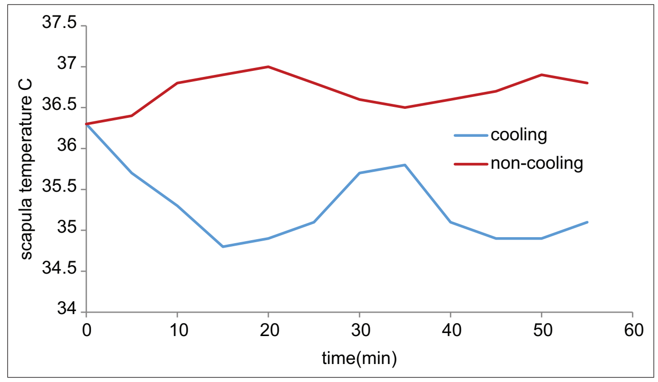

Figure 1: Trend of scapular skin temperature changes in the stage with and without cooling vest

Generator selection

According to the required voltage and amperage of the pump, a package including 6 lithium-ion batteries were built and used.

Cooling backpack

This part includes the cooling box, pump junctions, switches, and fittings attached to the vest. The box is made of a 2 L plastic heat-insulating space and occupies the least space due to the exact design of the backpack and box. 500 cc of water at a temperature of 4 − 5°C was poured inside the tank and two ice packs weighing a total of 500 g were used.

Phase 2: Evaluation of the active liquid cooling vest

Subjects

According to similar studies, 12 healthy male students participated in the evaluation of the cooling vest. This study was conducted based on the principles of ethics in the research, so at the beginning of the study, a written consent form was completed by subjects. The inclusion criteria included no history of cardiovascular disease, musculoskeletal disorders, seizures, epilepsy, pulmonary disease, neurological disease, diabetes, not consuming blood pressure and affecting heart rate (HR) medications, no caffeine, and alcohol 24 h before the study.

Tools

Measurement tools in this study included the following. The environmental parameters including dry bulb temperature, wet bulb temperature, relative humidity, and globe temperature were measured by the WBGT device (Casella, England). To measure HR, a Pulse oximeter (jax913, China) was used. Oral temperature (OT) and forehead temperature (FT) were measured using a laser thermometer (Bruer, Germany). Temperature sensors were also used to measure the skin surface temperature. At the end of each stage, participants were also asked to express their thermal sensation (TS) and perceived exertion (PE) based on visual charts.

Data collection

In the first stage, participants rested for 15 min in the rest room (24°C, RH 40%) and then HR, OT, FT, chest temperature (CT), and scapula temperature (ST) were measured and recorded as baseline data.

In the second stage, participants walked on a treadmill at a speed of 2 km/h at a 0° angle in the hot laboratory conditions (38.5, RH 40%). once wearing and once without wearing a ALCV [according to the protocol in Table 1]. The protocol consisted of four, 20-min phases, and rest periods consisted of four, 15-min phases that were done in rest room [Table 1]. To control the environmental conditions of the hot laboratory condition, WBGT index, dry bulb temperature, wet bulb temperature, and relative humidity were measured and recorded at 5-min intervals.

Data analysis

SPSS software version 16 was used for the data analysis. To check the data distribution normality, a data distribution test (Kolmogorov-Smirnov test) was used, and paired *t*-test was used to compare data in two testing conditions. $P < 0.05$ was considered as a significant level.

Ethical code consideration

This study was approved by ethical committee of Isfahan university of medical sciences (Ethics code: IR.MUI. REC.1396.3.468.).

Results

The result of the Kolmogorov-Smirnov test on all study parameters revealed that the data distribution was normal ($P < 0.05$). The values of environmental indices including dry bulb temperature, wet bulb temperature, and WBGT index [Table 2] show that environmental conditions are thermally stressful. Statistical test also showed that there is no significant difference between environmental parameters in the stage with cooling vest and the stage without its ($P > 0.05$).

Table 3 indicate the mean values of the scapula and chest skin temperature, HR, heat sensation, and intensity of perceptual activity while wearing the cooling vest and not wearing its. The results of paired *t*-test showed that there was a significant difference between the mean CT, mean ST, mean HR, mean TS, and mean PE in both conditions of using the cooling vest and not using its. However, the mean parameters of OT and forehead skin temperature with and without cooling vest were not significant [Table 3].

Table 1: The process of testing the active liquid cooling vest in the hot laboratory conditions

Time (min)	Position
0–20	Rest
20–40	Walking-no vest
40–50	Rest
50–70	Walking-vest
70–80	Rest
80–100	Sitting-no vest
100–110	Rest
110–130	Sitting-vest

Table 2: Mean, minimum and maximum values of environmental parameters measured in the hot laboratory condition

Environmental parameters	Test condition	Minimum	Maximum	Mean
WBGT index (°C)	Without vest	30.5	31.7	31.2
	With vest	31.0	31.9	31.6
Dry bulb temperature (°C)	Without vest	37.9	38.8	38.4
	With vest	38.2	38.9	38.5
Wet bulb temperature (°C)	Without vest	27.0	27.7	27.3
	With vest	27.2	27.9	27.6
Relative humidity (°C)	Without vest	39.0	41.8	40.0
	With vest	39.1	41.7	40.6

Table 3: Physiological and perceptual indices in cooling vest and noncooling vest conditions

Measured parameters	Mean±SD		*P*
	Cooling vest	Noncooling vest	
Scapula temperature	35.3±0.46	36.6±0.25	0.001
Chest temperature	34.4±0.58	36.5±0.29	0.001
heart beat	90.4±5.23	92.9±5.98	0.026
Oral temperature	36.5±0.36	36.4±0.39	0.45
Forehead temperature	37.0±0.18	37.0±0.33	0.84
Thermal sensation	1.6±0418	2.8±1.42	0.001
Intensity of perceived exertion	1.3±1.97	2.3±1.23	0.001

SD: Standard deviation

Based on the data of Figure 1, the mean scapular temperature in the stage of using the cooling vest is 35.07°C, and without using it, is 36.7°C. In the first 20-min period, the biggest difference in the ST in the stage of using the cooling vest and not using it is 2.19°C and 1.93°C in the second time interval. The smallest temperature difference in the Figure 1 is related to the restroom without using the cooling vest. The lowest scapular temperature in the stage of using the cooling vest is 34.8°C and the highest scapular temperature in the stage of not using the cooling vest accounted for 37.0°C.

Trend of CT changes is shown in Figure 2. CT has experienced an increase while the user is not using a cooling vest; otherwise, it saw a decrease while the user is using a cooling vest. The lowest temperature in the condition of using the vest is 34.4°C and the highest temperature in the condition without using it is 36.89°C. The lowest temperature decrease is observed during the 15^{th} min of activity and it experiences a gradual during the 35–55 min period.

There is no significant difference in HR in the two testing conditions. The mean HR experienced a steady trend in the test process. The mean HR did not exceed 101.8 bpm when not using the vest and did not exceed 98.1 bpm when using the cooling vest [Figure 3].

Based on the data of Figure 4, during the first 20 min, participants who were wearing the cooling vest felt 2.5 times better and more comfortable than those without a vest, and in the second 20 min, the difference was 1.5 times. During the rest time, the heat sensation in both groups is the same

The changes in the intensity of PE in the two groups with using and without using the designed cooling vest experienced almost the same trend and there is a difference of approximately 1.5 times [Figure 5].

Discussion

Environmental parameters measured in the hot laboratory condition including, WBGT index, dry temperature, wet temperature, and relative humidity were not significantly different in the two conditions of the test [Table 2], which indicates that environmental conditions are thermally stressful. Furthermore, in the both stages of the test were performed in the same environmental conditions and the measured parameters are affected by the cooling effect of the cooling vest. In this study, mean skin temperature at different parts (scapula and chest), HR, TS, and intensity of perceptual activity in cooling vest were significantly lower than none cooling vest condition [Table 3] There was no significant difference between the mean OT and FT in two stage [Table 3], but according to the trend in the diagrams, it is possible that by increasing the time in which user is wearing the cooling vest, there will be significant temperature differences.

While the user is wearing the cooling vests, the flow of blood through the surface of his skin cools and the heat transfer between the blood and the skin reduces the body temperature.[12] Since a change in body temperature can affect HR, a decrease in body temperature can result in a decrease in HR. Ice-gel cooling vests are likely to cause localized frostbite for the user.[11] In the meantime, it is possible to adjust the

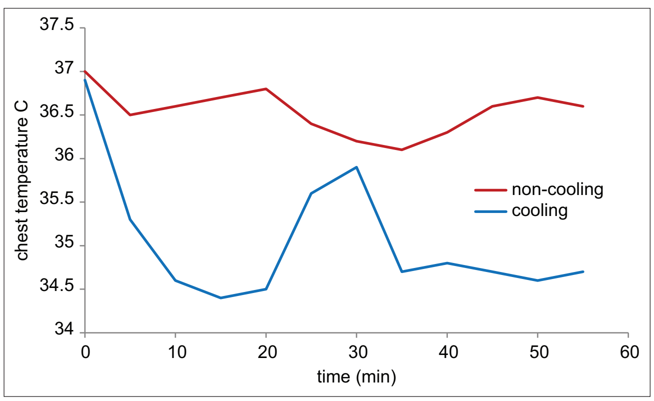

Figure 2: Trend of chest skin temperature changes in the stage with and without cooling vest

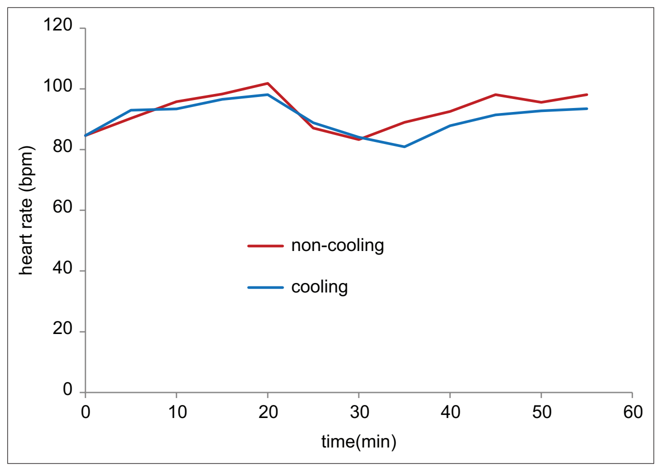

Figure 3: The trend of heart rate changes in the stage with and without cooling vest

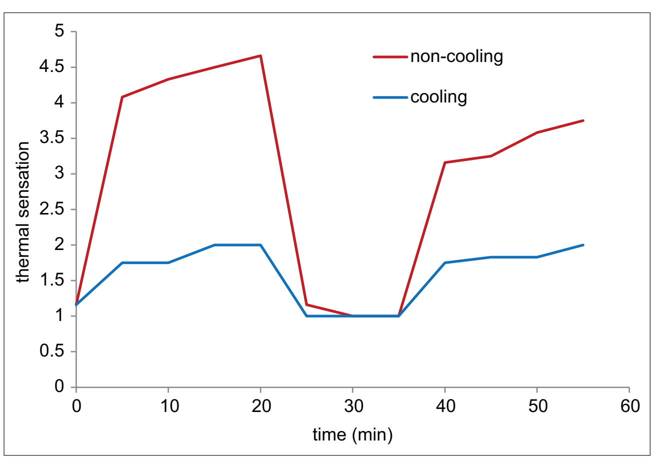

Figure 4: Trend of thermal sensation changes in stage with using and without cooling vest

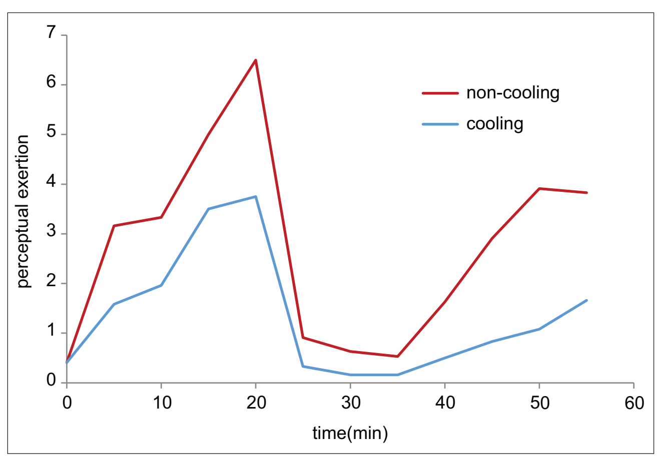

Figure 5: Trend of intensity of perceived exertion changes with using and without cooling vest

coolant flow rate inside the tubes in the designed active cooling vest sample, so the cooling rate is appropriate according to the different conditions.

In 2016, a study conducted by G. Bartkowiak aimed to investigate the performance of the ALCV at 30°C and 40% relative humidity, whereas the participants were doing an activity on the treadmill. It was found that there are significant differences between the mean skin surface temperature in the different parts of the body both in cooling vest inclusion and its exclusion conditions, which shows the high efficiency of the equipment.[13]

The trend of changes in OT experienced an increase and no significant difference was observed ($P > 0.05$) while wearing the cooling vest and the opposite situation. In 2020, a similar study was conducted on 10 students with an average age of 21 years in the laboratory condition (dry temperature 30° and relative humidity 40%) and activity on the treadmill by M. Yuan, to evaluate the effectiveness of an ALCV worn under an aluminum fireproof protective cloth. It was found that this vest did not have much effect on OT, but it had a significant effect on the average temperature of the skin surface in various parts, including the scapula, accounting for a 2.5 − 1.2°C decrease in temperature. In both studies, the cooling vest had a small effect on decreasing the HR.[11]

Comparing the ALCV with the commercial model of the VESKIMO brand, it can be stated that in the commercial model, there is no option for adjusting the coolant flow rate, therefore, the user sometimes experiences an annoying feeling of local cooling.[14] While in the current model, the possibility of adjusting the coolant flow rate through mini-valves connected to the inlet of silicone tubes eliminates the risk of local cooling, so the user is going to experience a better feeling.

Similar studies have been conducted on different types of PCM cooling vests by various researchers have produced similar results, in which the user experienced an improvement in the TS and skin temperature has reported to be reduced in different parts of the body when using the cooling vest in the stress room. For example, in a study conducted by Yazdani Rad *et al.*[15] on 31 male students in an hot laboratory (air temperature 40°C and RH of 40%) with both low and medium activity on a treadmill, the results showed that there is a significant difference between the average skin temperature and the TS of the participants when using a commercial paraffin vest with a peak melting point of 11°C and ice cooling vest and without its.[16]

Conclusion

The designed ALCV could significantly reduce the heat stress. The effective performance of new ALCV on the average surface temperature of the skin in the parts such as scapula and chest was remarkable. This cooling vest can adjust the flow rate. Therefore, based on the amount of heat in the work area, the cooling rate can be changed by changing the flow rate of the pump. In future studies to improve the performance of this type of cooling vest, the following suggestions are presented: Using Peltier elements to cool the water inside the box and the cold water box of the cooling vest can be designed in a way that the user can use it as a waist bag.

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Conflicts of interest

There are no conflicts of interest.

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