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Smart Solid-State-Based Device for Localized Thermal Therapy Applications

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Abstract: Compact, portable and low-cost health care solutions especially home-based health care has been the focus of research in recent years. Injury in sports such as sprain, strain, cramp and other muscle and tissue injuries are unavoidable. These injuries require pre- and post-medical treatment for faster recovery. There are three proven effective aids for faster recovery of patient with muscle and tissue injuries. First is compression – device with various wraps for arm, leg, etc. Second is localized thermal therapy – hot or cold for post-traumatic and post surgical conditions. And third is contrast therapy – automatically alternates from hot to cold therapy and vice versa. Localized thermal therapy such as hot or cold compress home-based health care is cheaper than hospital medication. It helps to reduces swelling, alleviates muscle spasms, stabilizes injured tissues and soothes and reduces pain. Conventional hot or cold compress devices are based on gel and therefore require heater and cooler. Hot compress uses steam and cold compress uses ice cubes to heat and cool the gel respectively. Aside from they are bulky, they are also disposable and that means higher cost for the patient. Lastly, they are not 'smart' device. They does not have interactive graphical user interface (GUI) for temperature control, timer, alert and alarm. This paper proposes a 'smart' solid-state-based device for localized thermal therapy applications. This device is comprised of solid-state thermoelectric module based on Peltier effect. It produces heat on one side by passing the current into the thermoelectric module (TEM), while it produces cold by reversing the current direction. It has no moving parts, so the solid-state construction results in high reliability. In heating mode thermoelectric module are much more efficient than conventional resistant heaters because they generate heat from the input power supplied plus additional heat generated by the heat pumping action that occurs. Device's controls are based on two microcontrollers (μCs) and have the capability for hot, cold and contrast compression. Smart GUI is developed using the NI's LabVIEW graphical programming software. High power solid-state driver is used to control the thermoelectric module to set into the desired temperature. The device is powered from commercial outlet by default but it can be also powered by a battery making it portable. The device is capable of reaching temperature of as low as 5˚C and as high as 60˚CThis temperature range is suitable for common muscle and tissue injuries acquired in sports. It is accurate (desired temperature point +/- 8˚C and faster to settle into the desired temperature (it takes less than 35 seconds from 5˚C to 45˚C or from 45˚C to 5˚C) with the help of feedback mechanism employed in the design.

Key Words: localized thermal therapy; smart hot or cold compress; solid-state thermoelectric module

1. INTRODUCTION

Compact, portable and low-cost health care solutions especially home-based health care has been the focus of research in recent years. There such portable health care monitoring devices like blood pressure monitor, heart rate monitor among many others which check and feed the data into the internet for analysis. Injury in sports such as sprain, strain, cramp and other muscle and tissue injuries are unavoidable. These injuries require pre- and post-medical treatment for faster recovery. Some known pre-medical treatments are hospital operations; while post-medical treatments are physical and physiological therapy. Localized thermal therapy such as hot or cold compress home-based health care is cheaper than hospital medication. It helps to reduces swelling, alleviates muscle spasms, stabilizes injured tissues and soothes and reduces pain. This paper focuses only on the post-medical thermal therapy of muscle and tissue injuries commonly acquired in sports.

1.1 Common Injuries in Sports

Globally known sports like basketball and football causes many injuries to the players. Muscle sprain, strain and cramp are among common injuries a player can acquire from these sports. In the event that one of these injuries happen, pre- and post-medical treatments are necessary. Pre-medical treatment can be operations of the tissue – and this is faster to finish. The post-medical treatment however will take longer time to complete as the muscle or tissue will try to regenerate or heal – and this is usually done at home. Figure 1 shows some of these muscle and tissue injuries. The first image shows icing the banged-up knee to avoid swelling; second image is a leg suffering from cramp; third is the hamstring pull due to hyper-extension; and the last is a runner anguishing from ankle sprain.

Figure 1. From left to right - (a) knee injury (b) leg cramp (c) hamstring injury (d) ankle sprain [Images were borrowed from the internet from various sources]

1.2 Therapy Modalities

There are three proven effective aids for faster recovery of patient with muscle and tissue injuries. First is compression – a device with various wraps for arm, leg, etc. Alternating right amount of pressure is applied in the injury. Second is localized thermal therapy – a hot or cold for post-traumatic and post-surgical conditions. The temperature and time which hot or cold compress is applied into the muscle injury will be prescribed by the physician. And third is contrast therapy – either automatically or manually alternates from hot to cold therapy e.g. 20 minutes at 10°C and 10 minutes at 40°C repeating continuously. Doctor's prescription is also necessary in this case. This paper focuses only on the localized thermal therapy and contrast therapy.

1.3 Benefits of Hot or Cold Compress

There are four major benefits identified when using hot or cold therapy. The first one is it reduces swelling. We usually seen live or in television that ones the muscle or tissue injury occurred in a sports game, a bag of ice or a heater is being placed and wrapped into the injured part of the body. Doing so will reduces swelling. Swelling will probably prohibit the operation later on. The second benefit is it alleviates muscle spasms. Cold compress promotes faster recovery of the injured muscle by easing the muscle contractions. Third is it stabilizes injured tissues. Lastly, it soothes and reduces pain. Hot or cold compress temporarily relieve and decrease the pain as it relaxes the muscle or tissue.

1.4 Conventional Hot or Cold Compress Solution

Since it was proven that hot or cold or contrast compress helped to promote fast muscle and tissue recovery for dost-medical therapy, there are conventional hot or cold compress devices or at least means of doing so. For example, there are these hot or cold compress devices that are based on gel such as shown in Figure 2. Such gel requires heating or refrigerating before it can be use for hot or cold compress respectively.

Figure 2. From left to right – (a) gel pack of hot compress (b) gel pack of cold compress [1]

For hot compress, gel needs to be steamed. For cold compress on the other hand, gel needs to be refrigerated. Sometimes ice and ice bag is being used for cold compress. Both gel and ice solutions are disposable – that means it incurred higher cost. They are also not "smart" e.g. does not have temperature control, timing, etc. The amount of heat and cold deteriorates with time. Moreover, they are bulky – that means they are not portable. These abovementioned problems of the conventional solutions unlock the idea of developing a solid-state-based hot or cold compress device for localized thermal therapy.

2. METHODOLOGY

This paper proposes a 'smart' solid-state-based device for localized thermal therapy applications. The device is comprised of solid-state thermoelectric module based on Peltier effect. The device was prototyped, tested, and the results were analyzed. Parameters such as power consumption, and time required to change the temperature of an object were approximated based on the obtained results and were discussed in this paper in the results and discussions section.

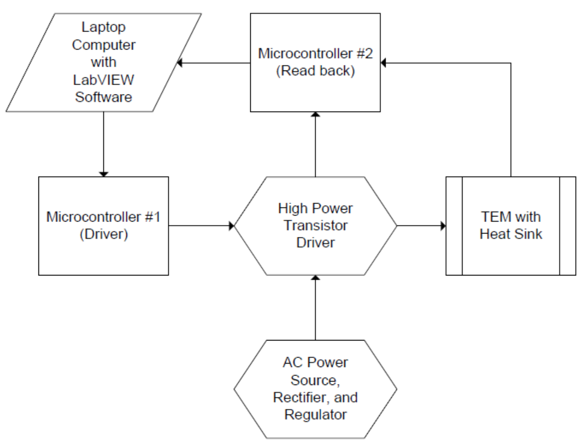

Figure 3. Functional block diagram of the proposed hot or cold compress device

Shown in Figure 3 is the block diagram of the proposed hot or cold compress device. Commercial power is the default source of this device but it can be also modified to get power from battery to make it portable. AC power is converted into 12V DC with capability of up to 6A current drive. Two microcontrollers are used in the design. One of them controls the high-power transistors that drive the TEM, while the other one is used to monitor or read back the temperature from the . Each of these μCs has their own software and algorithm which being controlled and called by the GUI. GUI is developed using graphical programming language LabVIEW. The device operates in close-loop mode. When the desired temperature is set, the driver μC turns on the transistor driver so that the TEM will start to reach the desired temperature. The other μC monitors the TEM's temperature and report the state to the GUI. The GUI determines when to turn on or off the driver. The error window is set to +/-4˚C. Equations 1 and 2 are used to calculate the temperature points (maximum and minimum) that the TEM can be acquired. For example if you desire a hot temperature point of 40˚C, you can expect that the TEM will output temperature that varies between 38˚C and 42˚C.

$$Max\_T_S = T_D + T_E \quad \text{(Eq. 1)}$$
$$Min\_T_S = T_D - T_E \quad \text{(Eq. 2)}$$

Where:

Max_T_S - Maximum temperature that can be acquired
Min_T_S - Minimum temperature that can be acquired
T_D - Desired temperature point
T_E - Expected window of error

2.1 What is Thermoelectric Module?

The Peltier effect is not new. In fact it was discovered back in 1834 but it was not commercially feasible before the semiconductor process is perfected and commercially available. Thermoelectric modules or simply TEMs are solid-state heat pumps that require a heat exchanger to dissipate heat utilizing the Peltier effect. During operation, DC current flows through the TEM to create heat transfer and a temperature differential across the ceramic surfaces, causing one side of the TEM to be cold, while the other side is hot. When the current is reverse it produces, it also reverses the hot and cold side. Once the current can be controlled and the one side can be held in a stable temperature by the use of heat sink, then the temperature on one side can also be controlled making this pump useful in many applications.

The actual construction of a typical TEM is shown in Figure 4. It is made up of several numbers of P- and N-type materials. P-N nodes are electrically-connected in series but thermally-connected in parallel. Therefore, the same TEM can be used as a heat pump or a voltage generator (also known as Seebeck effect or thermocouple effect). TEM is indeed amazing.

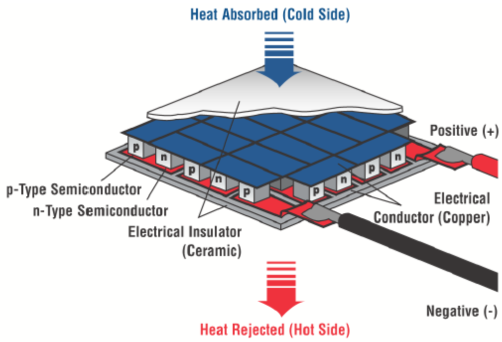

Figure 4. Construction of a typical TEM [2]

2.2 Solid-State-Based Hot or Cold Compress Device

Device's controls are based on two microcontrollers and have the capability for hot, cold or contrast compression. High power solid-state driver is used to control the thermoelectric module to set into the desired temperature. The device is powered from commercial outlet by default.

Figure 5 shows the complete setup of the device. A regulated 12V DC and 6A maximum current is supplied into the TEM through H-bridge driver. The direction of the current is being controlled by the μC #1 and it gives either hot or cold temperature on the one side of the TEM. A current sense is inserted before the TEM to monitor the amount of current being drawn by the module during the operation. The μC #2 is used to read back the actual temperature of the TEM and being feed backed to the computer that runs the program. If the temperature is not yet settled on the set point, it either increases or decreases the amount of current of the TEM. The TEM is assembled in a plastic box. Notice the heat sink on one side of the TEM. Its purpose is to stabilize the temperature on one side (un-used side of TEM) at 25˚C as much as possible – this is called reference temperature. That is when the 45˚C hot temperature is desired for example, one side needs to increase only by 20˚C. The same thing happen when 5˚C is desired, one side needs only to decrease by 20˚C. It is important to note that the reference temperature varies with the type of heat sink. When small heat sink will be use, there will be chance that the reference temperature will vary directly proportional to the desired temperature (increasing or decreasing temperature) and therefore there will be chance that the desired temperature will not be meet or it will take longer time to meet.

Both microcontrollers are connected to the computer via universal serial bus (USB) interface. The computer runs the software that controls everything about the device. The software is designed and the interactive GUI is developed using LabVIEW. LabVIEW fetches the data from the two μCs, process and analyze, and takes necessary actions from there on.

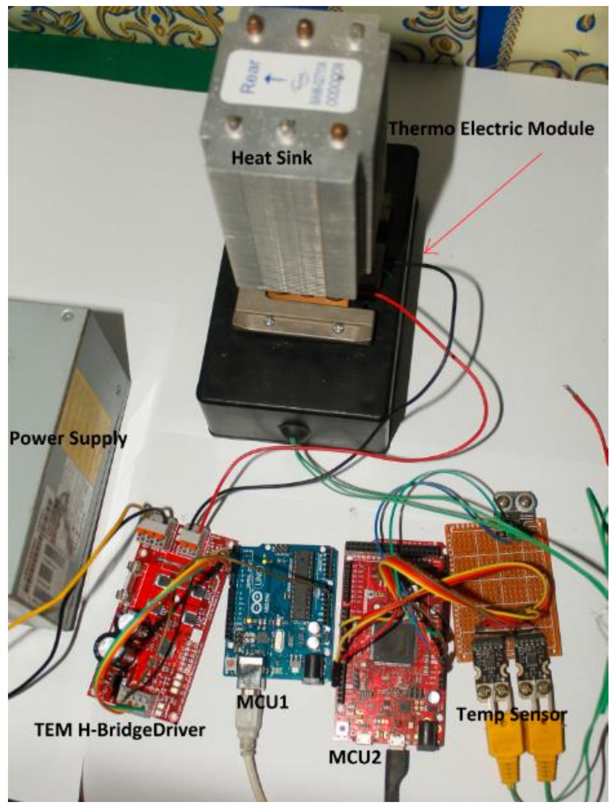

Figure 5. Complete prototype setup of the solid-state-based hot or cold compress device [3]

The complete block diagram of the device is shown in Figure 6. This shows the interconnections of the device. In this case, Atmel μCs present in Iduino Duo and Arduino Uno are used but they can be replaced with any μCs available in the market with the same capabilities.

The μC board #1 uses ATmega328, an 8 –bit microcontroller. The μC board #2 uses Atmel SAM3X8E ARM Cortex-M3. The TEC driver is Darlington pair and has the current drive capacity of 6A. ADC is 12 bit SAR. TEM module is TEC1-1206 standard thermoelectric device. There are two temperature sensors used – MAX31855. Their inputs are analogue signals while their outputs are digital signals in serial form.

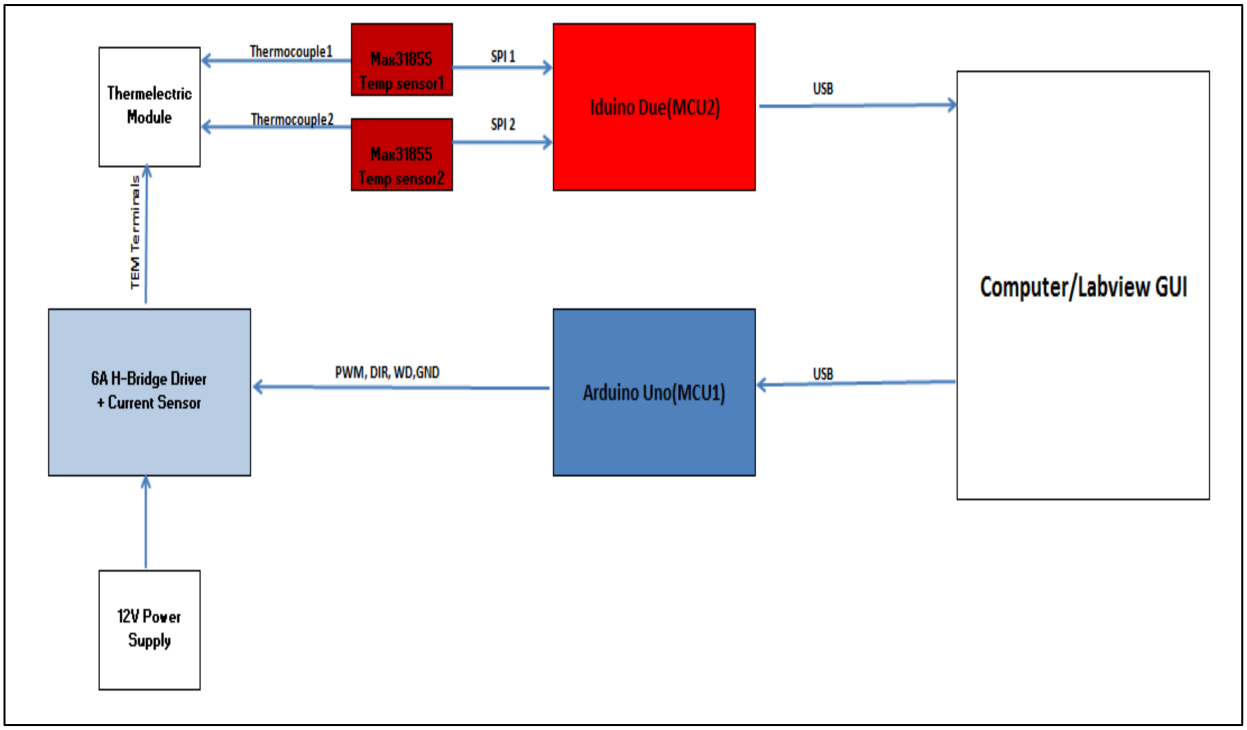

Figure 6. Block diagram of the device [4]

2.3 Programming Algorithm

Two separate programs are developed that controls the two µCs. One program is to control the driver and the other one is to read back the current drawn and read back the TEM's reference and desired temperatures. Programs for TEC driver and temperature sensor are quite long to append in this paper. One might ask a copy of them by sending a request email to the authors (email address can be found just below the title).

2.3 Making the Device Smart

Smart GUI is developed using the NI's LabVIEW graphical programming software. The two µCs programs describe in subsection 2.2 is being called in LabVIEW. Read back data is analyzed and necessary action is taken sequentially. The GUI has a smart function, that is by the employment of pre-defined codes for a certain injury – in this case ankle sprain. An ankle sprain is a muscle injury which requires hot or cold compress and/or contrast compress. The physician will prescribe the appropriate method of therapy and the patient will follow it at home as part of post-medical treatment. By the use of this smart GUI, the patient only needs to press the 'Ankle Sprain' button and the pre-programmed therapy will be then executed and there's nothing more the patient needs to do. The GUI is programmable in such a way that all the therapies necessary for any muscle and tissue injuries will be pre-programmed. This will significantly aid the patient for precise therapy.

Figures 7a, 7b and 7c are the snapshots of the front panel of the GUI (it is quite large). The first thing the user needs to do is to 'Run' the program. Then, he has the option for 'Manual" or 'Smart' therapy. If 'Manual' therapy is selected, he needs to key-in the desired temperature and hit enter. Otherwise, if the 'Smart' therapy is chosen, he just needs to select what type of injury he has (for now the choices are 'Sprain' and 'Strain') and then hit enter. Both therapy options can be terminated instantly by hitting the 'Stop' button. Finally, on the right side of the GUI are the graphical indicators of the TEM's temperature and sensed current. This is useful for software diagnostic purposes. It is also shown in Figure 7c the temperature chart. It indicates the current and actual temperature of the TEG.

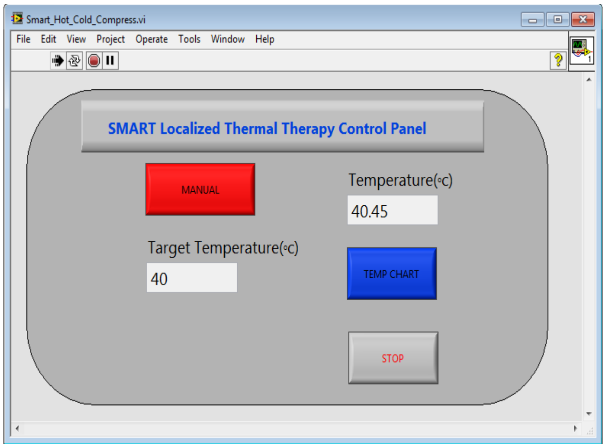

Figure 7a. Front panel of the GUI – Manual

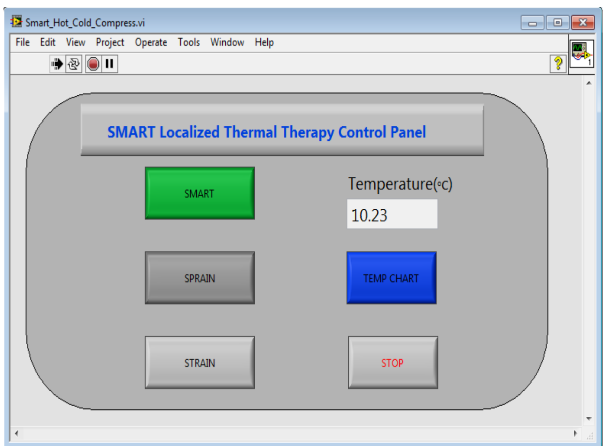

Figure 7b. Front panel of the GUI – Smart

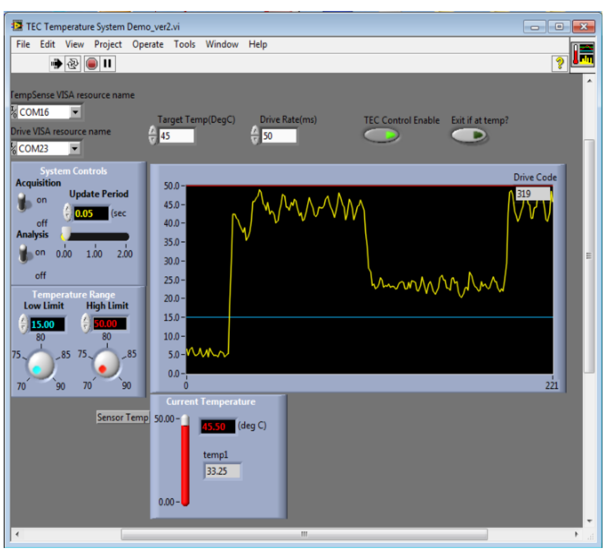

Figure 7c. Front panel of the GUI – Temp Chart

3. RESULTS AND DISCUSSION

After the device is set up, testing and characterization are the next tasks. With all the components listed is section 2.2, the following results are obtained. It is worthy to note that different components, especially the kind of heat sink, will probably yield to different result and it is not covered in this paper. Furthermore, the TEM surface requires isolation material before it can be apply to the skin. The said material is currently being explored.

3.1 Device Performance and Test Result

As the result of test, the device is capable of reaching temperature of as low as 5˚C and as high as 60˚C. However further study is needed that at this high temperature there are no harmful effects into the skin. It is recommended only in this paper that the maximum temperature one can be se is 45˚C only. This temperature range is suitable for common muscle and tissue injuries acquired in sports. It is accurate (desired temperature point +/-4˚C and faster to settle into the desired temperature (it takes less than 35 seconds from 5˚C to 45˚C or from 45˚C to 5˚C) because of feedback mechanism employed in the design. During normal operation, maximum current consumption is around 416mA. This is equivalent to a power consumption of 5W (with a supply of 12V).

This paper proved that it is possible to have a device that uses neither gel nor ice. This device can be also design to be portable by the use of battery and portable monitor instead of power supply and computer. In addition, TEM's temperature can be adjusted without replacing the module itself but by just tweaking the program. However, Arduino development environment and LabVIEW software licences are necessary before one can do so.

3.2 Temperature versus Power Consumption

The device is characterized and the result can be seen in Table 1. From this result one can determine what power he needs to reach the desired TEM's temperature. This helps the user to optimize the performance of the device with respect to his specific applications.

Table 1. Summary of characterization result

Run	TEM's Temperature	Temp Overshoot/Undershoot(DegC)	Accuracy(DegC)	Ripple Amplitude(DegC)	Current(ARMS)	Time(sec)	Transition Power Consumption (W)	Comments
1	40C to 5C	- 1	+/-2	+/-4	-1.56	35	7.8	~27 sec from 40DegC to 5DegC, Max current at 1st 3 sec
2	40C to 10C	- 1	+/- 5	+/-4	-1.51	30	7.55	-0.34 after it settles
3	40C to 15C	- 1	+/- 5	+/- 1	-1.52	20	7.6	-0.34 after it settles
4	40C to 20C	- 1	+/- 3	+/- 1	-1.52	20	7.6	-0.34 after it settles
5	40C to 25C	- 1	+/- 1	+/- 1	-1.52	15	7.6	-0.34 after it settles
6	25C to 30C	+1	+/- 3	+/-2	0.38	10	1.9	-0.04 after it settles
7	25C to 35C	+3	+/- 4	+/-2	1.52	20	7.6	-0.34 after it settles
8	25C to 40C	+5	+/- 5	+/-2	1.54	15	7.7	-0.34 after it settles
9	25C to 45C	+5	+/- 8	+/- 1	1.55	15	7.75	-0.34 after it settles
10	25C to 50C	+5	+/- 8	+/-4	1.55	20	7.75	-0.34 after it settles

3.3 Advantages of the Proposed Device over the Conventional Solution

The following are the rationale why user should consider the proposed device over the conventional solution:

1. Solid-state-based hot or cold compress device has no moving parts, so the solid-state construction results in high reliability.
2. TEMs can cool devices down to well below ambient. Thermoelectric are able to heat and cool by simply reversing the polarity, which changes the direction of heat transfer.
3. In heating mode TEMs are much more efficient than conventional resistant heaters because they generate heat from the input power supplied plus additional heat generated by the heat pumping action that occurs.
4. If properly design, its final package is small making is suitable for compact applications.

3.4 Recommendations of the Study

Even though the device is verified functional and met the target specifications, the authors would like to recommend the following which they believe further improve the design:

1. To make it portable, battery is needed as power source. However during the development of the device battery which has specifications of at least 5V, 1000mAh is not at hand. Also, its socket or adaptor is lacking. Thus it is recommended to modify the power source – from commercial power source to battery.
2. The heat sink used is bulky and will not fit with the strap when apply to the injury. Thus it is recommended to replace it with slim-type with more or less the same heat dissipation capability.
3. The TEM itself is not yet ready to apply directly into the skin or injury as it is required to have insulation between the TEM and the skin to avoid burns. The authors are currently looking for a possibility of using gel or any suitable insulator.

4. CONCLUSIONS

It is concluded that a solid-state-based device for localized thermal therapy applications is successfully designed, developed and tested. With the used of appropriate components together with sophisticates programming, the device is successfully prototyped. The device is capable of reaching temperature of as low as 5˚C and as high as 60˚C. This temperature range is suitable for common muscle and tissue injuries acquired in sports. It is accurate and faster to settle into the desired temperature because of feedback mechanism employed in the design. Recommendations are also given to further the future study.

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