Alleviation of Arthritic Symptoms through Thermal Therapy

S.A. Ayala, T.O. Hamid, A.H. Shah, A.A. Trivedi, B.F. BuSha
The College of New Jersey
2000 Pennington Road
Ewing, NJ 08628

***Abstract*—Arthritis is a leading cause of disability among U.S. adults; from 2010-2012, an estimated 52.5 million U.S. adults annually have been diagnosed with arthritis. While symptoms vary from patient to patient, the majority are faced with tender, painful, and swollen joints, and reduced strength and overall hand function. Options for short-term relief are currently limited, especially for patients with intense pain following prolonged rest. Consequently, patients are often forced to endure physical therapy sessions over several weeks, costing them both time and money. The therapeutic arthritic glove (TAG) corrects these issues by delivering automated cycles of heating and cooling to the hand specified by the user. The goal is to alleviate arthritic symptoms associated with prolonged rest, explicitly pain and swelling. Heat flux is provided by thermoelectric coolers, and regulated by an Arduino microcontroller and ten thermistors. Coolers are placed between the PIP and the DIP joints of the index, middle, ring and pinky finger and the MCP joint of the thumb.**

Keywords—thermoelectric, cooling, heating, Peltier, arthritis, glove, cooler, rheumatoid, osteoarthritis, Arduino

I. INTRODUCTION

Arthritis is the leading cause of disability among U.S. adults, with approximately 52.5 million affected nationwide, or 22.7% of the total population. This prevalence is magnified in adults over the age of 60, with a diagnosis rate as high as 49.7%. By 2040, an estimated 78 million US adults are projected to have some form of arthritis, or 32% of the population [1].While problematic symptoms vary based on the diagnosis, the majority of patients are crippled with tender and swollen joints, joint stiffness, joint pain, reduced range of motion and flexibility, and otherwise reduced overall hand function. The most problematic symptoms are experienced following prolonged rest, especially in the morning following sleep.

Current devices available to patients with arthritic symptoms in the hand are limited. Continuous passive motion devices are devices offered by clinical offices to aid in resistance training. However, these devices can be expensive, ranging from $3000 to $10,000. Furthermore, there currently exists no device that offers active heating and cooling to patients suffering from short-term symptoms, such as pain and inflammation, due to arthritic joints in the hand. The TAG alleviates these symptoms through heat and cooling delivery using Peltier modules. Through localization of heat transfer to the affected areas, the device aims to reduce and alleviate short-term symptoms common to arthritic patients, such as pain and swelling.

II. METHODS

In general, the most impacted joints in patients with arthritis are the distal interphalangeal (DIP) and the proximal interphalangeal (PIP) joints of the index, middle, ring and pinky finger, as well as the metacarpophalangeal (MCP) joint of the thumb [2]. While affected joints vary from patient to patient, coolers were placed between the PIP and DIP joints of the four main fingers and the MCP of the thumb to design for the most common scenario. Nylon was selected as the glove material due to greater thermal conduction and decreased possibility of allergic sensitivity or reaction relative to other materials, as well as purchasing convenience.

Thermistors were placed on the skin surface area surrounding the thermoelectric cooler footprint at the DIP and PIP joints as well as the MCP of the thumb to continuously monitor skin surface temperature. Studies on limits of thermal tolerance by NASA reveal that the onset of pain occurs at 15ºC at an exposure time of 5 minutes. Similarly, the pain threshold for heat in the hand was found to be 44ºC at an exposure time of 8 minutes. [3]. Microcontroller control ceases thermoelectric operation when these temperatures are reached on the skin surface. Furthermore, a manual emergency-switch is placed on the device if the user wishes to terminate device operation.

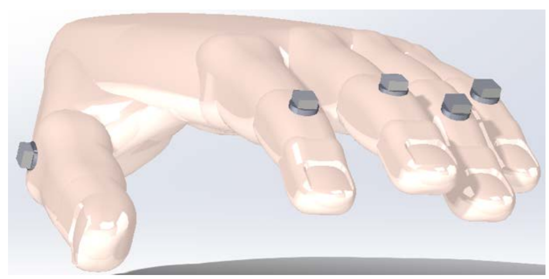

Figure 1: SOLIDWORKS Model of T.A.G. Glove Design

Tipton et. al inspected the maximum radiative and convective heat transfers from each hand and foot to the surrounding air in ambient air temperatures of 15ºC and 45º C, and reported a respective loss of 16.6 W and gain of 18.1 W [4]. Assuming the heat transfer is uniform throughout the entire hand, this power can be divided by the total blood volume in the hand and multiplied by the individual finger volume to obtain total heat transfer required for the aforementioned temperatures of an individual finger, as shown in Eq. 1.

$$\frac{W_1}{m^3} * m^3 = W_2 \quad (1)$$

This absolute power can allow for selection of compact thermoelectric modules to move the heat sufficient to bring the fingers to these temperatures. Size constraints were considered based on the smallest average finger width of the human hand. According to anthropometric measurements made by the Civilian American and European Anthropometry Resource, the average pinky is approximately 0.5 inches in width, or 12.7 millimeters [5].

Therefore, the modules cannot be greater than 12.7 millimeters in width. 10mm x 10mm coolers were selected based on cost and aforementioned size constraints.

Heat transfer required for various individuals using the glove was determined through the development of a linear relationship between height, total hand volume and individual finger volume. Eleven test subjects, five males and six females, were evaluated based on the total surface area of the hand. Surface area measurements were taken at each finger and the dorsal side of the hand, and multiplied by the thickness of each respective area to compute an estimated overall hand volume. Volume measurements were then compared to heights of each subject to compute an equation that correlates these parameters. Total blood volume measurements were then correlated to the volume of each individual finger.

Using subjects evaluated for determination of the correlation between height, hand volume and finger volume, the range obtained for heat transfer of an individual finger was found to be 1.416-1.869 W for men and 1.298-1.715 W for women.

Using Eq. 2, the cold and hot side temperature necessary for heat extraction and supplication can be calculated, where T is temperature, t is thickness of the glove, k is thermal conductivity and A is area. The nylon glove selected in this application is 0.22mm thickness.

$$Q = \frac{\Delta T}{\frac{t}{kA}} \quad (2)$$

Using Eq. 3, the amount of heat required for appropriate dissipation was determined, where Q_L is the heat extracted from the cold side of the cooler and W is the work done by the module. This allowed for the selection of 30 mm x 30 mm fans and aluminum heat sinks of the same size. Q_H is heat generated from the hot side of the cooler. The temperature of the hot side can then be calculated using Eq. 4, where h is the heat transfer coefficient of the surrounding medium.

Assuming the fan is placed directly on top of the heat-sink, heat dissipation is similar to an impinging jet heat transfer model. Using this model, the heat transfer coefficient can be related to Nusselt number, shown in Eq. 5, where L is the length of the impinging plate and k is the thermal conductivity of the fluid. The Nusselt number can then be correlated to Reynolds number and Prandlt number for air, shown in Eq. 6. Finally, the velocity of the air can be computed using Eq. 7, where this velocity is multiplied by the effective area of the fan to find the volumetric flow rate of air required to move the waste heat from the module.

$$Q_H = Q_L + W \quad (3)$$

$$Q_H = hA\Delta T \quad (4)$$

$$Nu = \frac{h*L}{k} \quad (5)$$

$$Nu = 0.729\, Re^{0.5} Pr^{0.4} \quad (6)$$

$$Re = \frac{pvd}{u} \quad (7)$$

Initial testing was completed using the chosen thermoelectric coolers on a hand analogue. Jacobson and co-workers demonstrated that gelatin can be a suitable substitute for plasma in experiments involving experimental shock [6]. Due to cost constraints, gelatin was molded inside of a nitrile glove, which was considered negligible in heat transfer analysis due to its thin nature.

III. Results

Output temperature was modeled as a function of time over a 20 minute interval. Step responses for heating and cooling were modeled as second and first order responses, respectively, using Simulink and MATLAB. Output functions for the cold side response and hot side response are shown in Eqs. 8 and 9, respectively. Internal hand temperatures, on average, reached 41.2° C ± 4.6 and 18.9° C ± 4.1 C with maximum and minimum temperatures of 44.6 and 15.1° C.

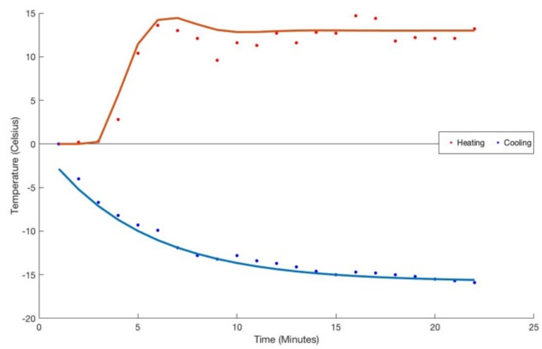

Figure 2: Normalized Internal Temperature Change of Hand Analogue Exposed to 15°C and 44°C Peltier Module.

$$H(t) = 15.789 * e^{-\frac{19t}{95}} + 31\delta(t) - 15.789 \quad (8)$$

$$H(t) = 31\delta(t) - (e^{1.568} - 0.56t)\left(\frac{\cos(20.71(t-2.5))}{25}\right) \quad (9)$$

IV. Conclusion

This device was designed with the intent of alleviating short-term symptoms of arthritis in the hand associated with prolonged rest, specifically pain and swelling. Recommended treatment for these symptoms is repeated thermal therapy, with alternating hot and cold application. Heat flux to and from the hand was accomplished through Peltier modules placed between the PIP and the DIP joints. Waste heat was dissipated using aluminum heat-sinks and fans. Overall system control was provided using an Arduino microcontroller and ten thermistors.

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