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Liquid Cooling System for the Vibro-tactile Threshold Device

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Abstract— **Vibrotactile threshold testing has been used to investigate activation of human somatosensory pathways. A portable vibrotactile threshold testing device called the Vibrotactile Threshold Evaluator for the Workplace (VTEW) was designed for screening of carpal tunnel syndrome in the workplace, and initially contained a small fan for cooling. During subject testing, the device is operated intermittently, which causes the linear actuator to warm the tactile probe. The probe causes discomfort for some subjects. During testing, the probe heated to 42°C within 90 seconds of continuous operation. A liquid cooling system was implemented to dissipate heat from the probe. The liquid cooling system maintains a steady state temperature of 36°C for continuous actuation of the probe. The liquid cooling system is capable of maintaining a safe operating temperature, without adding erroneous vibrations to the device. However, the cooling system deters the portability of the device. Further research will investigate how to make the liquid cooling system portable and implements vibrotactile threshold testing in the workplace to quickly evaluate whether or not a person has early symptoms of carpal tunnel syndrome.**

I. INTRODUCTION

VIBROTACTILE threshold testing is a versatile tool for detecting peripheral neuropathies. Peripheral neuropathy is a symptom of nerve damage which causes numbness and tingling in the extremities [1,2]. Nerve damage can be caused by either chemical exposure (chemotherapy), mechanical compression (carpal tunnel syndrome), or metabolic disorders (diabetes). The focus of this research is evaluating nerve damage caused by carpal tunnel syndrome (CTS).

CTS is most commonly an occupational disease, costing $20 billion in workers' compensation annually and 31 days of lost work per case [3]. The incidence of CTS among the general population has been shown to be increasing over the past two decades (Fig 1). For employers, musculoskeletal disorders associated with repetitive and forceful motions of hands and wrists are the second-largest contributor to the costs of workers' compensation (following injuries of the back) [3]. CTS is caused by a compression of the median nerve within the carpal tunnel in the wrist, which causes a loss of tactile sensation in the fingertips. The current standard diagnostic test for CTS is the nerve conduction velocity test (NCV). The NCV test uses an electrical stimulus to measure the action potential speed of the median nerve to detect nerve damage and requires a trained technician. Since CTS is an occupational disease, there is a need to quickly evaluate symptoms of CTS in the workplace to prevent prolonged nerve damage from work related repetitive hand motions.

The vibrotactile threshold evaluator for the workplace (VTEW) at the University of Utah will be used for workplace trials to collect information about early warning signs of median nerve damage, to investigate prevention of CTS in the workplace. A portable vibrotactile threshold device to be used in the workplace can cost-effectively and quickly screen for symptoms of CTS [5]. In the workplace scenario, efficient access to regular evaluation of nerve health has advantages for both workers and employers. VTEW affords the opportunity to monitor nerve health on a regular basis, which allows symptoms of CTS to be identified early (and confirmed with methods such as NCV), with a resulting reduction in the number of cases of CTS requiring surgical intervention.

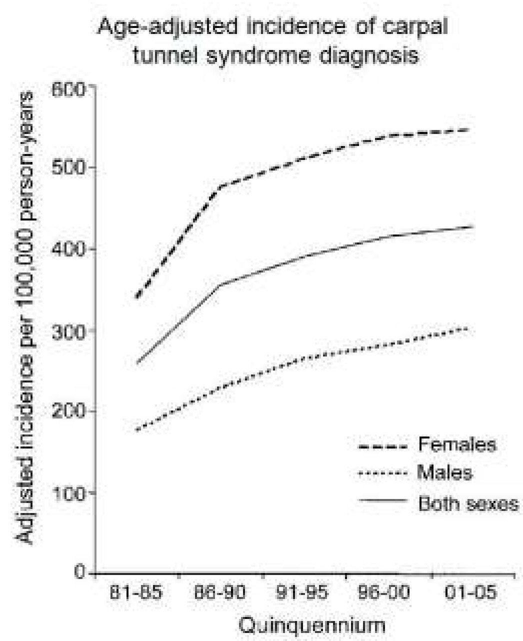

Fig. 1. Age adjusted (women, men) and aged and sex adjusted (both sexes combined) incidence per 100,000 person-years for carpal tunnel syndrome diagnosis from 1981-2005 among Olmsted County, Minnesota residents [4].

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The VTEW could be used for regular evaluation in the workplace, unlike the NCV test. NCV equipment is expensive (typically >$15K) and requires a trained clinician to administer the exam. In addition, it can cause minor discomfort, and thus is not well suited for regular evaluation. Conversely, a device such as the VTEW is low-cost (prototype <$2.5k), and the diagnostic test lasts 5-10 minutes. It could be self-administered after a one-time short training (<15 minutes).

Vibrotactile threshold testing uses tactile perception to evaluate median nerve damage. Tactile perception is sensed by mechanoreceptors (MRs) underneath the skin surface [1,6]. MRs are activated by a vibratory stimulus, which is converted to electrical signals (action potentials) that are conducted through the central nervous system. The sensory threshold is determined by the user's perception of stimuli at varying frequencies and step sizes. Subjects with CTS have a higher vibrotactile threshold due to median nerve damage [5,7].

The ergonomic design of the VTEW platform provides arm support for the user during testing (Fig 2). Each diagnostic test lasts approximately five minutes per user. The user places a finger innervated by the median nerve (index or middle) of their dominant hand on the stimulus probe of the device. The probe oscillates at a given frequency and step size, and then decreases with varying step sizes, beginning with a high step size. The purpose of decreasing the step size of the probe is to determine the threshold, which is found when the user no longer perceives a vibration. In order to find the minimum step size that the user can perceive, the step size is increased and subsequently decreased about the threshold, following the method of limits protocol.

During preliminary testing, some users experienced discomfort from the probe stimulus overheating. One of the concerns of temperature increase in the probe, other than discomfort for the user, is inaccuracy of threshold measurements. An increased temperature of MRs has been shown to change the tactile perception [2]. The scope of this work includes modifications to the initial design to maintain a constant probe temperature during evaluation.

To keep the probe from overheating, a liquid cooling system was designed and mounted to VTEW. Cooling systems use thermal conductivity or convection to maintain a desired temperature of electrical systems. Fans or liquid cooling systems are commonly used for desktop computer central processing units (CPUs) because they are quiet and inexpensive. The VTEW was previously cooled through air convection with a fan. A fan using air convection is not as efficient as liquid convection cooling [9]. Furthermore, the fan produced extraneous vibrations within the device, which may cause errors in the testing process. The liquid cooling system is low cost, does not produce erroneous vibrations in the device, and is a more efficient means of heat transfer than the fan cooling system alone.

The remainder of this paper describes the hardware and the experimental results of the cooling system. Section II summarizes the VTEW and the liquid cooling system. Section III reports the temperature control results of the liquid cooling system. Section IV compares the liquid versus the fan systems, and suggests improvements to the liquid cooling system design.

II. Hardware

A. Vibrotactile Threshold Evaluator for the Workplace

The VTEW was designed and built in the BioInstrumentation Lab at the University of Utah to detect early peripheral neuropathy signs due to CTS. The motivation for the design of the VTEW was to create a CTS test that can be easily conducted in the workplace with accuracy and repeatability. The VTEW has three essential components: probe, surround, and actuator. The stimulus probe is in direct contact with the subject's index finger, the surround is concentrically aligned with the probe to provide a concentrated contact location of the probe, and the actuator vibrates the probe at various frequencies and amplitudes.

Unlike most commercially available vibrotactile testing devices, the VTEW is capable of achieving a wide range of stimulus probe vibration frequencies (1-500 Hz) [10]. The

Fig. 2. The Vibrotactile Threshold Evaluator for Workplace Screening (VTEW) with the cover removed to show the surround and probe [8].

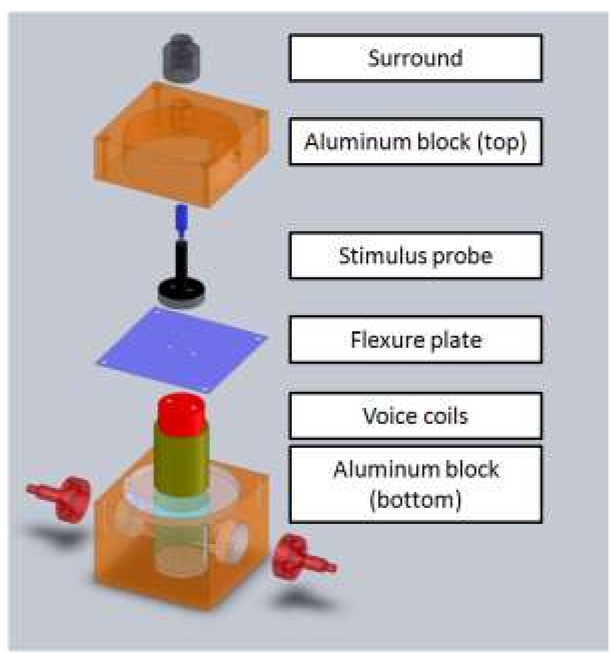

Fig. 3. Exploded assembly of the voice coil actuation. The aluminum block, the aluminum flexure plate, and the aluminum stimulus probe are conductively linked.

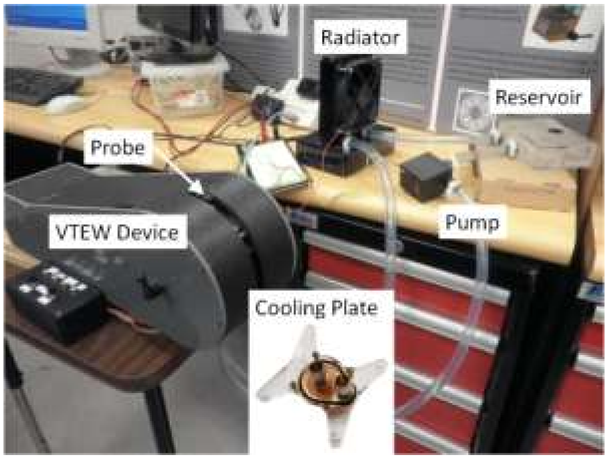

Fig. 4. Liquid cooling system cycle: reservoir, pump, cooling plate, radiator, reservoir. The copper cooling plate is mounted underneath the VTEW to the aluminum block.

frequency variability is important to recruit different types of MRs and to study the effects of CTS on different sensory pathways. For example, a frequency of vibration lower than 6 Hz recruits only slow-adapting MRs, whereas a frequency between 16-100 Hz will target rapidly-adapting MRs [11]. Isolating the type of MR response will obtain a different threshold for various frequencies, providing information about which neural pathways are damaged.

The surround and the diameter of the probe play an important role in threshold detection. The VTEW has an adaptable probe diameter (2-10 mm). A small probe diameter can isolate the contact location on the fingertip, and the surround provides support for the remaining area of the fingertip. The surround isolates the effects of the probe vibration on the contact location only, because skin stretch and depression is dampened underneath the surround [12].

A linear voice coil actuator vibrates the probe in a sinusoidal waveform with an amplitude of a certain step size. A LabView interface drives the actuator with closed loop control of the step size and the frequency of vibration based on an optical position encoder feedback. The 5VDC voice coil is embedded in a 9x9cm aluminum block that supports the probe (Fig 3). The aluminum block is able to rotate between 0-120° in order to test various angles of wrist flexion on tactile threshold. The heat dissipated from the voice coil is conducted through the aluminum block and to the probe.

A two interval forced choice method is used for the testing protocol of the VTEW. Two intervals, one with stimulus and one without, are indicated by a user friendly input device. The user selects the one interval with the stimulation. Upon answering correctly, the step size is decreased at a fixed interval. Upon answering incorrectly, the tactile threshold of the user is found using a method of limits protocol by increasing the step size and subsequently narrowing in on the minimum threshold step size perceived.

B. Cooling system

The ergonomic design of the VTEW resulted in the linear actuator being embedded within an aluminum block. The voice coil of the linear actuator generates heat proportional to electrical current. The aluminum block absorbs and stores the dissipated heat energy, subsequently causing the stimulus probe to rise in temperature. Initial testing resulted in the users experiencing discomfort due to temperature on the tip of the finger.

Cooling the aluminum block can cool the probe because they are conductively linked. The aluminum block is attached to the aluminum flexure plate, which directly attaches to the aluminum probe. The low specific heat capacity (765 J/kg K) causes the aluminum block to hold the thermal energy over long periods of time. In addition, the high thermal conductivity of aluminum (46 W/m K) can provide an effective means of thermal energy dissipation. Therefore, the conductive link between the block, the flexure plate, and the probe can be used to dissipate thermal energy throughout the system.

The liquid cooling system was modified from a standard CPU cooling kit. All materials were supplied from the Danger Den Introduction Cooling Kit. The operating liquid is distilled water with a corrosion blocker additive. The liquid cycle flows from a reservoir through a 12 VDC pump, to a copper plate mounted on the aluminum block, through a radiator, and finally back to the reservoir (Fig 4). The copper plate is mounted to the aluminum block with thermal compound between the surfaces, to improve the efficiency of conductivity. The radiator and the pump are connected in parallel with a 12 VDC battery connected in series with a switch.

The addition of the copper cooling plate mounted underneath the aluminum block required modifications to the VTEW design. Due to size limitations, the surrounding Plexiglas on the copper plate was removed. Mounting holes were drilled through the copper plate and into the aluminum block. In order to maintain the full 120° of rotation of the block, the bottom panel of the VTEW was modified. The half inch tubes connected to the cooling plate interfered with the surface of the table, so the VTEW was elevated with pieces of wood.

C. Data collection

The difference between the fan cooling system and the liquid cooling system were measured over time during continuous actuation of the VTEW. In order to achieve a maximum thermal energy dissipation from the voice coils, the VTEW was operated at a continuous frequency of 50 Hz for 30 second intervals. In order to achieve a steady-state resting temperature, the power to the coil and the cooling system were turned on before temperature measurements began. The temperature of the probe tip and the aluminum block were recorded before and after each 30 second interval. All temperature measurements were evaluated using a type K thermocouple (+/- 0.5°).

III. Results

The liquid cooling system maintained a constant probe temperature of 36°C when operating in a 17°C room temperature with a 50 Hz vibratory frequency. Without

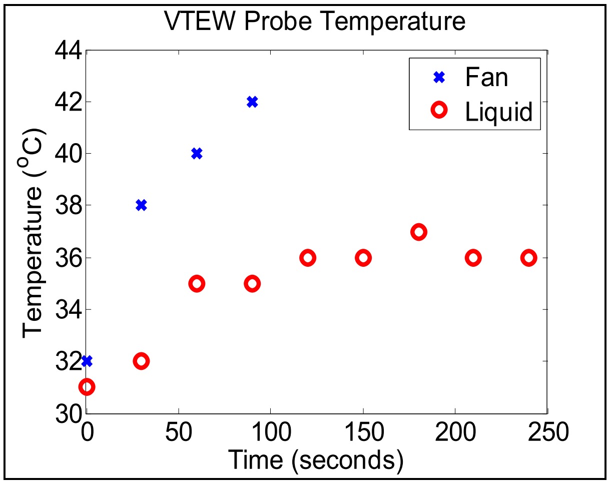

Fig. 5. Probe temperature results for the fan and the liquid cooling systems. The temperature of the probe with only the fan cooling exceeded 42°C, so the data collection was stopped to prevent thermal damage to the VTEW.

vibratory actuation and only a constant 5 VDC supply, the liquid cooling system maintained a probe temperature of 31°C at rest, while the fan cooling system resulted in a 32°C steady state temperature. The heat dissipation from a constant voltage supply and no continuous actuation can be maintained at a comfortable operating steady state temperature.

The continuous operation of the stimulus probe was maintained at a vibratory frequency of 50 Hz. The operating temperature of the probe reached 42°C within 90 seconds of continuous operation without the liquid cooling system (Fig 5). In order to prevent thermal damage to the VTEW, no further data was collected at continuous operation without the liquid cooling system. The liquid cooling system achieved a steady state temperature of 36°C after approximately 100 seconds of continuous operation (Fig 5). The steady state temperature was maintained for 600 seconds of continuous operation. The aluminum block temperature was consistently 22°C for both the liquid and the fan cooling systems.

IV. CONCLUSION

The liquid cooling system significantly decreased the operating temperature of the stimulus probe by more than 6°C. Furthermore, the continuous operation without the liquid cooling system does not achieve a steady state temperature within 90 seconds. The liquid cooling system effectively reduces the operating temperature of the stimulus probe during continuous actuation.

The stimulus probe overheating not only causes discomfort to the user, but may influence the MR response. The MRs are recruited based on variable frequencies, but the velocity of the axons traveling through the central nervous system is dependent on temperature. Maintaining a constant temperature of the stimulus probe is important for accuracy and repeatability of vibrotactile threshold measurements. Further indication of the benefits of the liquid cooling system could be evaluated by measuring sensory threshold for users both with and without the liquid cooling system. We would expect to see a change in thresholds due to the change in probe temperature. For future research, the VTEW will be actuated until maintaining a constant temperature of the stimulus probe, therefore reducing external factors on threshold measurements.

The cooling system does not create erroneous vibrations that directly communicate with the stimulus probe. Removing the fan from the aluminum block assembly reduces the risk of adding erroneous vibrations to the stimulus probe and obtaining an inaccurate tactile threshold reading.

The portability of the VTEW is a necessary requirement for testing in the workplace. Therefore, future research will assemble a Plexiglas casing mounted underneath the VTEW. The pump and the radiator will be isolated in a dampening material (e.g. rubber) prior to assembling the cooling system underneath the portable VTEW in order to reduce the effects of erroneous vibrations on the system.

Although the liquid cooling system impedes the portability of the VTEW, it can effectively maintain a comfortable steady state temperature of the stimulus probe and decrease the risk of external factors influencing the tactile threshold measurements. Improving the portability of the cooling system is critical before using the VTEW in the workplace in order to allow workers and employers to conveniently evaluate nerve health.

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