Over-Use Warning Glove for Carpal Tunnel Syndrome

Mariam Ayrapetyan, Wenny Miao, Kellen O'Rourke

Augmenting Human Dexterity – Spring 2021
Term Project Report

Abstract

Two interviews of patients with Carpal Tunnel Syndrome (CTS) are conducted and analyzed. This interview analysis is described and used to formulate a novel approach to the detection and prevention of CTS symptoms. A glove with embedded pose and muscle sensors is used in combination with an alert system to warn the user during overuse. A preliminary warning algorithm is described and relevant data from a prototype glove is provided. Additionally, a proposed study to test the efficacy of this device is provided. The data collected from this device can be used to expand our understanding of CTS symptoms and disease progression. This paper concludes with a vision of a future product which packages the sensors and warning system into a smartwatch accessory.

I. Introduction

Carpal Tunnel Syndrome (CTS) is an extremely common neuropathy that affects between 1 and 5% of the US population [1]. Specifically, women, older adults, and desk workers are at a higher risk of developing CTS [2]. The disease is caused by elevated pressure in the wrist usually due to performing a set of repetitive tasks. People with CTS experience pain and weakness in their hands which typically requires surgery to alleviate. As such, to avoid surgery, early detection and prevention is important and has the potential to improve the lives of millions.

A. *Background*

Highly repetitive, high-force motions, and to a lesser extent awkward hand and wrist postures have been connected to increased prevalence of CTS development and progression [3][4]. This has become increasingly relevant, as several studies have shown that computer use, which involves "forceful finger and wrist flexion and extension", as well as "postural stress" can contribute to CTS development [5] [6]. Symptoms of CTS include "pain, numbness, or tingling on the anterior surface of the index, middle or radial half of the ring finger", which can often be exacerbated by certain hand and wrist activities [7]. In fact, in a subgroup of CTS cases known as "latent" or "dynamic" CTS, symptoms completely "subside with rest and return with repetitive motion" [8]. The increase of symptoms with activity can be explained anatomically as repetitive motions may cause thickening of the synovial linings of tendons that run through the carpal tunnel [8]. In addition, certain positions of the wrist, such as flexion and extension, increase carpal tunnel (CT) pressure and may impair blood flow to the median nerve [9].

Because the natural history of CTS is still not well understood, and "symptom frequency and intensity do not correlate well with objective pathophysiology", treatment often focuses on symptoms rather than measurable pathophysiology [10][11]. The best methods for CTS treatments remain controversial. Surgical decompression is considered to be the definitive treatment of the condition, however conservative treatment may be recommended for patients in less severe cases, without signs of significant progression [12]. Many different types of non-operative treatment are available for those who prefer to avoid surgery, including splinting, corticosteroid injections, oral medication, hand therapy, ultrasound therapy, and acupuncture [1]. The efficacy of these methods remain debatable due to lack of data available, as well as bias in results due to "risk and lifestyle factors" changing after treatment without being registered. In addition, several studies have shown "an important percentage of cases resolving without any specific treatment"

[11]. Despite the fact that there clearly remains much to be understood about CTS, it is generally agreed upon that performing repetitive, high-force motions increases risk of the condition worsening in severity. Thus, CTS patients are commonly recommended to take frequent rest breaks from repetitive jobs, perform stretching exercises, and use correct posture and wrist position when performing tasks[13]. Symptom onset can also be very gradual, starting with only numbness and tingling in the fingers before progressing to severe pain, increasing the risk of over-use before symptoms are noticed by the individual [13].

Several studies have attempted to analyze dynamics that may be considered higher risk for the development and progression of CTS. For example, by analyzing the carpal tunnel pressure associated with different postures of the hand, which has been identified as "a likely mechanism in the development or aggravation of CTS", Keir and colleagues identified wrist posture threshold angles that may be used to protect against nerve injury [14]. In addition, a study by Silverstein and colleagues on occupational factors for CTS development defined quantitative thresholds for the meaning of "highly repetitive" and "high force" jobs as those with "a cycle time of less than 30 seconds or more than 50% of the cycle time involved performing the same kind of fundamental cycles" and "estimated average hand force requirements of more than 4 kg", respectively, and correlated these categorizations with CTS development [4]. These studies have been useful in the design of ergonomic devices as well as informing interventions in the "worker-exposure-disease cycle" [4], however, the specific motions and postures that trigger CTS symptoms in a particular individual is highly case-specific and dependent on severity. Thus, more personalized motion, force, and posture guidelines, based on individual patient data, may be useful in reducing symptoms and preventing progression for each individual patient.

Motion capture gloves present a unique opportunity to capture this data. They have used in a great variety of applications, including controlling tele-operated robotic systems [15], recording sign language [16], and assisting in rehabilitation exercises [17]. These systems have also made use of a large assortment of different sensors, ranging from optical fiber sensors [18] to thin film strain gauges and pressure sensors [19]. In particular, the CyberGlove® has been gaining traction in its ability to record joint angles with high accuracy with a streamlined design [20]. The majority of these gloves, however, were not designed for long-term wear and data collection, and may be intrusive when performing daily work and activities. In addition, though clinical applications for these gloves have been proposed, such as for monitoring Rheumatoid Arthritis [21] and in analyzing ergonomics [22], the implementation of these systems is still lacking, and, to date, no such glove has been devised specifically for use in patients with CTS.

B. *Overview*

As described in section I-A, frequent breaks from repetitive jobs, and performing tasks with proper posture are some of the best ways to slow the progression of CTS. It follows that early detection of bad posture and overuse are of upmost importance to patients with CTS. We hypothesize that hand pose and muscle activity data can be used in combination with a user alert system to identify and prevent actions that cause CTS symptoms. Section II provides an analysis of two interviews with CTS patients that illuminates the difficulties associated with identifying and preventing overuse. The proposed device is described in Section III, and consists of a glove including IMU and EMG sensors, a micro-controller, and LEDs which recognizes overuse and warns the user. It will be used to study the efficacy of this wearable alert system. This testbed could then be used to gather data about disease progression. This is described in Section IV. As described in Section V, the results from this study could be the basis for a smartwatch accessory with a miniaturized version of this prototype. This product could help millions of CTS patients to slow the progression of their disease, and reduce the symptoms they experience.

II. Motivation

Two hour-long interviews were conducted with CTS patients to identify customer needs for designing a human-centered product. The structure of the interview followed the contextual inquiry method where users are asked questions and observed in their usual work environment. The details of this method can be further enquired at [23]. Nonetheless, COVID-19 constraints set few limitations to this method; in-person visits to the interviewees were disallowed and interviews were conducted remotely via Zoom. The structure of our interview consisted of an introduction of the interviewers and their goals, as well as questions about diagnosis, treatment, and device interactions.

The first interviewee was a female undergraduate student in her twenties who picked up crocheting and knitting last summer during quarantine. Her pain started to build up in the matter of weeks. She decided not to consult with a doctor for few reasons, one of which was because during the pandemic it was difficult to schedule an appointment with a physician, and another being that she believed that the pain would go away if she waited and rested. Instead, following the recommendations of her parents, she received a few sessions of acupuncture in which thin needles were inserted into her wrist. However, she described it was "like taking an Advil"–only a temporary solution. Typing and holding heavy object, as well as anything that required coordinated motion and bending of the wrist became painful for her. This led her to switch to an ergonomic keyboard and mouse, as well as use a wrist brace and an arm sling. However, as was discovered, some of these devices had disadvantages. For instance, they were hard to put on, sweat would accumulate during summer, and typing was only possible using one finger on the injured hand. She also mentioned something that later influenced the project idea substantially, that "treatment did not necessarily help, just doing things in moderation."

Thw second interviewee is an older adult in her fifties working as a college counselor. She acquired CTS over the years through the kind of job that she performed. Regular daily activities such as washing dishes or holding a knife became hard for her. Unlike our first interviewee, she decided not to wait to see a doctor. She was diagnosed with CTS after she received a corticosteroid shot. She went through multiple treatment options including occupational therapy, and purchased devices such as an ergonomic mouse pad, a glove with a pillow at wrist, and a firmer brace. She also had similar issues with these devices—struggling with buckling her splint and rendering her incapable of perform any kind of work. So, after all kinds of efforts to alleviate her CTS pain, she decided that surgery was the right alternative.

Both interviewees had a tendency to perform activities which worsened their symptoms of CTS. For example, the first interviewee would not notice less severe symptoms and continue knitting and crocheting to the point when pain became unbearable. Disregarding small signs such as short-term small pangs of pain and tingling in the fingers led to a breaking point after which cooking, typing, and moving items became impossible—she could not do any of her work. On the other hand, the second interviewee had to engage in typing activity as this was a regular part of her job responsibilities. She did not have an alternative means of performing the same task; as a result, the continuous engagement in this activity led her to develop severe CTS. In addition to typing, activities such as washing dishes, holding tools, and cooking also contributed to her condition worsening. She described a situation when she did gardening for the entire day, after which she felt excruciating pain. The pain was not present during the time in which she was performing these activities, but instead came suddenly and all at once afterwards. The conversations with the interviewees also revealed that doctor visits, scheduling appointments and actually getting treatment for CTS can take months, especially during COVID-19 pandemic. All the data and results gathered during the interviews and their analysis led the team to converge on pain preventive gloves.

Customer Statement	Interpreted Need
"Completely overlooked the kinds of pain I had in the wrist once in a while, didn't really think much of it"	Device helps keep track of wrist pain/pressure levels
"I think it was making sure I wasn't overstraining my wrist, than any treatment I got (accupuncture)"	Device prevents overstraining of wrist
(Didn't go to a doctor) "It was half because I thought I could wait it out, and didn't feel like I could go to a doctor in the middle of COVID"	Device does not require doctor visit
"I cannot cook, I cannot work, I cannot do daily activites, I just have to sit and rest with that thing on."	Device doesn't prevent daily activites (cooking/working)
(soft brace) " I like that it's so easy to put on and off... its like a sock."	Device goes on and off with one hand and without outside help

Fig. 1. Top 5 user needs chart. These needs were the most influential in the design of our glove.

III. Methods

This device is designed to be compliant and easy to don, allowing users full range of motion. It is made of soft fabric with small sensors and actuators sewn in. A waterproof fabric will be included as an external layer to prevent snags and protect the electronics. The glove will include two sets of sensors to provide muscle flex and wrist pose data over time, as both have been shown to contribute to increased carpal tunnel pressure and thus increase risk of CTS development and progression. The location of muscle sensor placement will be carefully described to the user, as it should measure the activity of the nine muscles whose tendons run through the CT (the flexor pollicis longus, the four flexor digitorum superficialis and the four flexor digitorum profundus) [24]. Additionally, the glove will include a FSR for the user to input pain information, and a LED and vibration motor to provide feedback to the user. The LED will provide information on how close the user is to over-straining their wrist, and the vibration motor will provide alerts as to when over-use is imminent, corresponding to LED color transitions.

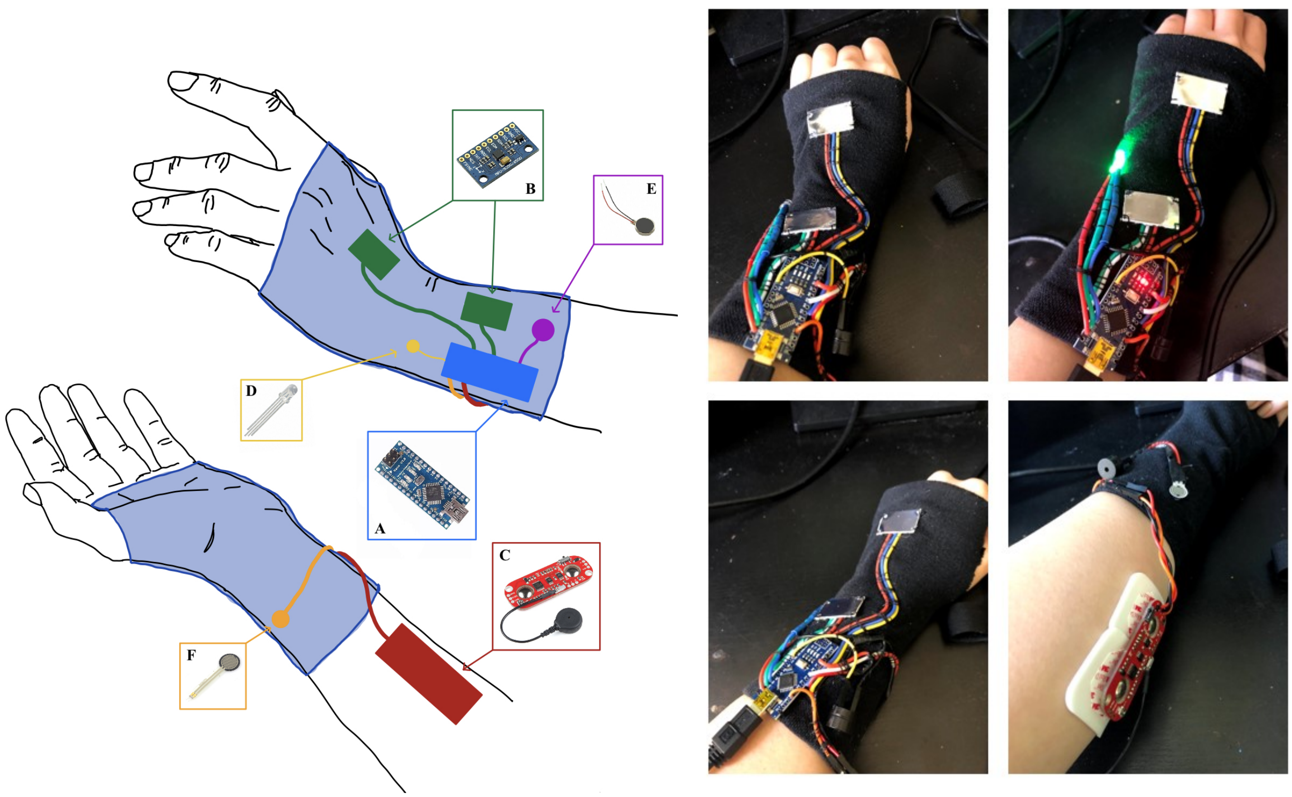


Fig. 2. (Left) Prototype setup with micro-controller (A), two gyroscope and accelerometer units (B), EMG sensor (C), RGB LED (D), vibration motor (E), and FSR (F). (Right) Physical realization of prototype.

Wrist angle is measured by comparing orientation measurements between two IMUs placed on the dorsal side of the hand and wrist. This method of wrist pose estimation is appropriate, as it does not limit range of motion and does not require a mechanical linkage. Additionally, the IMUs will provide bulk hand orientation and acceleration data, which can be used to further differentiate between tasks and provide additional information for training the glove. In addition, muscle activity will be tracked through the use of the MyoWare Muscle Sensor (Advancer Technologies), which measures the electrical activity of muscles (EMG) [25]. To obtain the best signal, the electrodes should be placed along the middle of the muscle body—in our case, the optimal location would be on the anterior, ulnar side of the forearm, approximately halfway between the wrist and the elbow. Because the muscles of interest are deeper in the forearm, sensor readings will likely experience interference due to the activity of the more superficial forearm muscles. However, this data should be sufficient in our application, to gain a general understanding of muscle activation. The logic behind device functionality is explained in Figures 3 and 4.

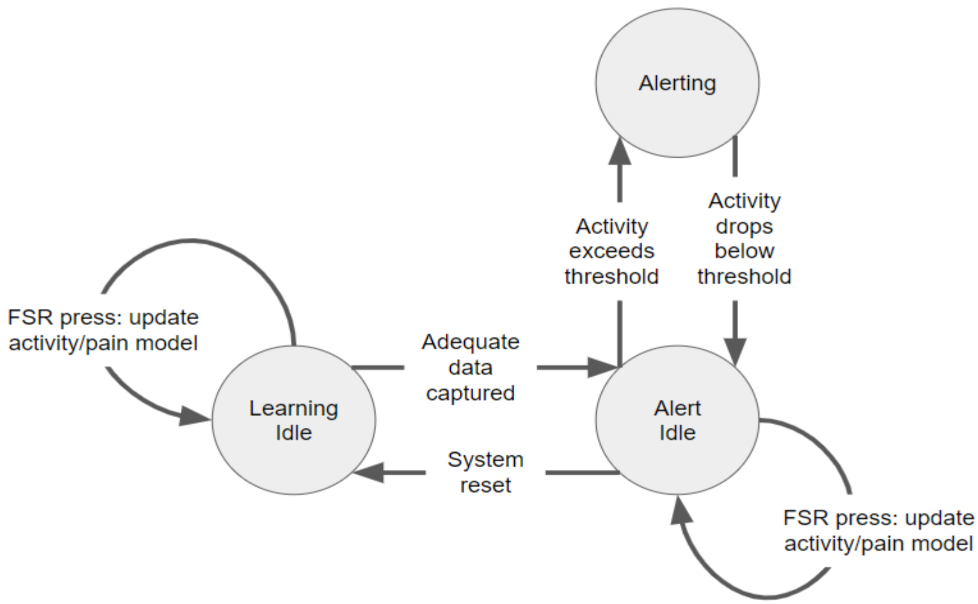


Fig. 3. Prototype finite state machine. This diagram shows the high-level device logic. The glove begins in the "Learning Idle" and moves to the "Alert Idle" once there is adequate EMG and IMU data. The LED is activated and remains on during the "Alerting" state. Additionally, the vibration motor is pulsed for 1 second between state changes.

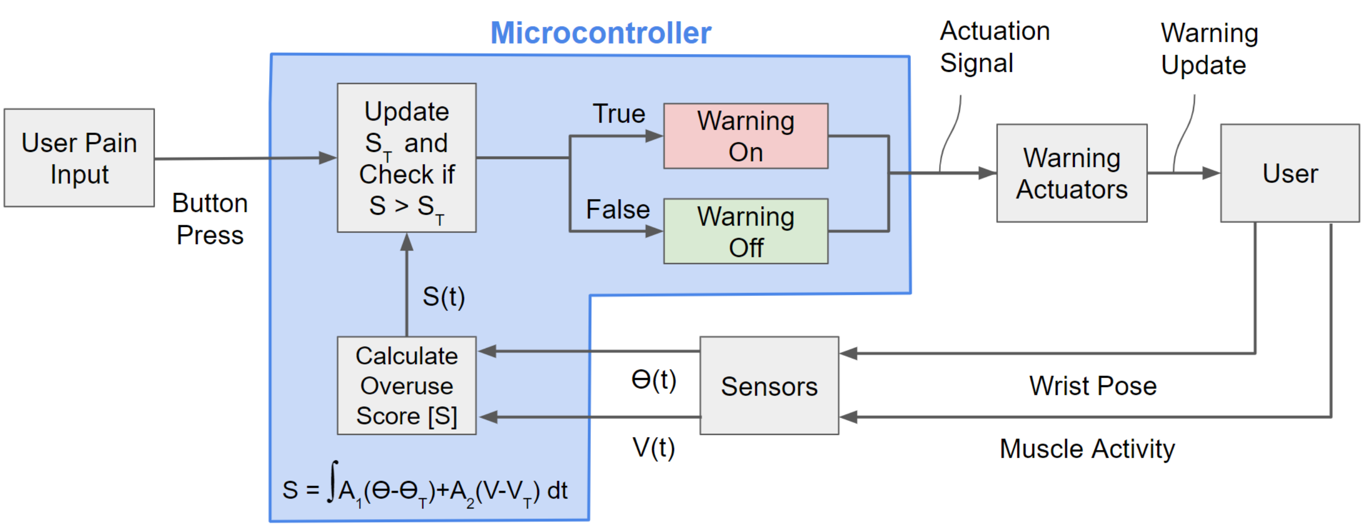


Fig. 4. Prototype overuse detection and alert algorithm. This diagram provides a more detailed description of the algorithm used to switch between "Alert Idle" and "Alerting" states in Figure 3. S_T is the Overuse Score Threshold. This variable is increased/decreased depending on if user pain input occurs before or after $S > S_T$. Θ_T and V_T are wrist angle and EMG voltage thresholds chosen based on literature [14] and a device study. A_1 and A_2 are scoring constants chosen based on a device study.

For this device to function, thresholds must be set for when the user should be alerted to rest their hand. Initial thresholds may be set according to values found in literature, as we have done in our prototype, shown in Figure 5. However, due to the highly variable nature of these values, a calibration period is needed in which users would input through the FSR when they feel pain. This data may then be analyzed to determine correlations between motion/postures and symptom flare ups, and used to adjust the alert thresholds. The thresholds can continue to be fine-tuned as the user is able to continue entering pain information, allowing the system to be further calibrated specifically for each individual, and allowing thresholds to evolve if the condition continues to progress. To determine the efficacy of this device, a long-term study should be run to compare the symptom severity and condition progression in three independent groups: one without the device completely, one with the device but without alerts, and one with the device and receiving alerts.

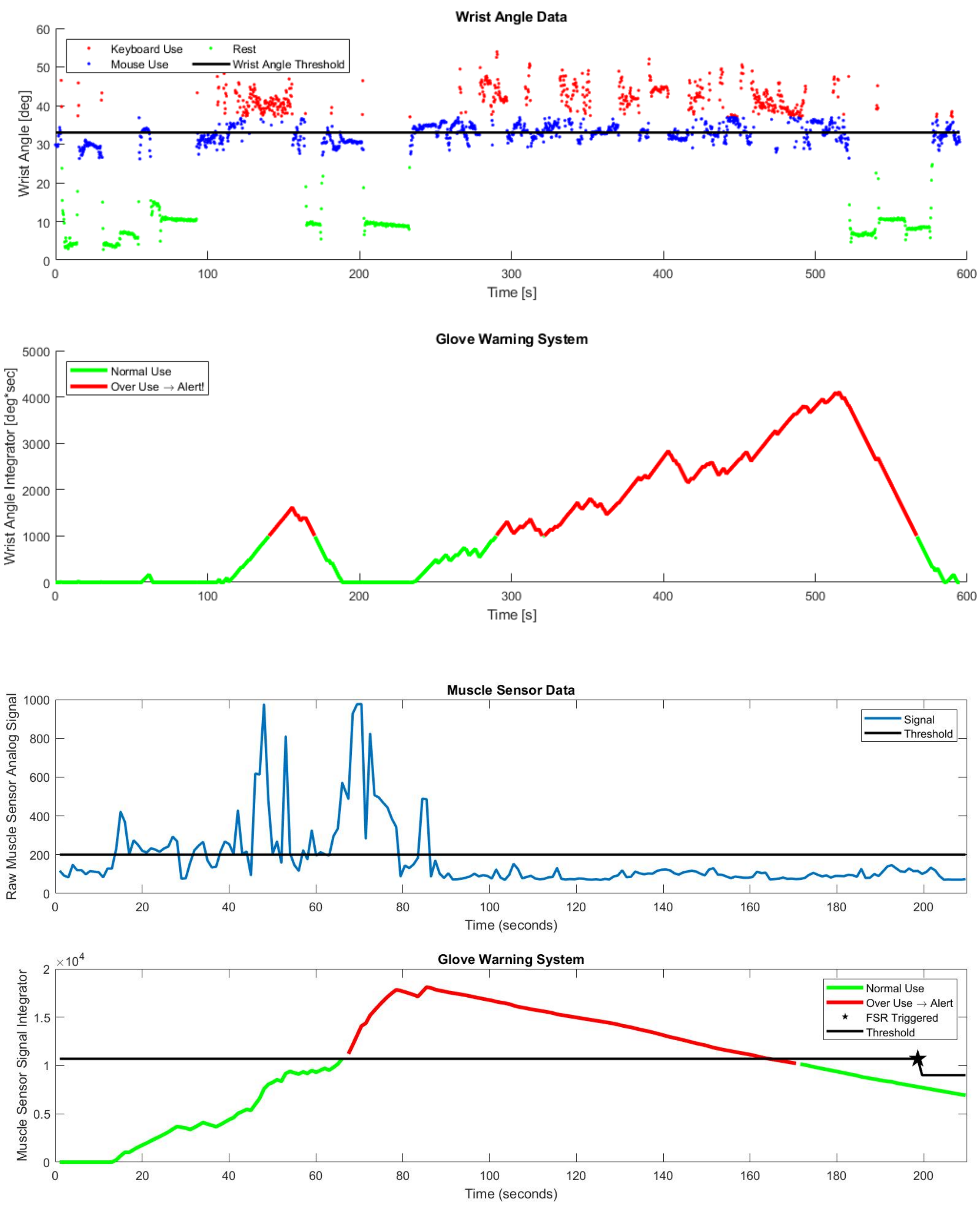


Fig. 5. Example of data collection and thresholds with alert triggering for IMU (Top) and Muscle Sensor Data (Bottom). Sensors are tested separately as hardware was split between team members, but will be combined in final product. Bottom-most plot shows decrease in threshold accompanying FSR pain input

Individuals diagnosed with CTS that have not yet undergone surgical release should be recruited for the study and divided into the three trial groups. Efforts should be made such that each group has an even distribution in terms of condition severity, occupation, sex, age, medical history, and non-surgical treatments undergone. Because our device does not present any inherent risk to the user, a pilot study is likely unnecessary, as its main purpose is to determine preliminary safety [26]. Instead, conducting a pivotal study, with 150 to 300 patients, is more appropriate to determine device efficacy. Because of the often slow progression of CTS, the study would need to be conducted over a long period of time, ideally two years at minimum, as in the study by Ortiz et. al. [11]. Individuals should be evaluated periodically through a physical examination, patient interview, and nerve conduction test. To prove the effectiveness of the device, a significant difference must be seen between the alert group and the other two groups in terms of symptom relief and condition progression. Comparison with the group not wearing device will reveal the impact the alerts have on the patient, compared to just the presence of the glove.

IV. Intellectual Merit

As mentioned in section I-A, the development of CTS in terms of symptoms and severity varies greatly between individuals, with spontaneous recovery occurring without treatment in a number of cases that cannot be disregarded. The efficacy of the many possible non-surgical treatment options also remains unclear due to lack of data, and because it is not known if ”risk factors (for example accumulative trauma) or lifestyle factors were changed without being registered in some patients” [11]. Because we do not limit, but do record the type of treatments the patients may or may not choose to undertake at each examination, such as overnight bracing, injections, or medication, and document many risk and lifestyle factors through collection of movement and muscle data, our study could prove extremely beneficial in understanding the progression, natural history, and pathophysiology of the condition.

V. Broader Impact

The idea of “Movement Detection Glove” was born from careful consideration of customer needs, concerns with current devices, and their limitations, therefore, it is a customer-centered product. It was designed to alleviate pain but at the same time enable the patient to perform work in a permissible amount. Patients with CTS will no longer have to wear uncomfortable splints or experience intense pain from overwork. Additionally, the device will prevent the disease progression since, as was discovered in the needs-finding, patients tend to overlook their symptoms and put extra stress on their wrists. Ultimately, this device has a potential to substantially reduce pain and even reverse CTS development. This device may also prove to be useful in understanding other conditions of the hand. Future work may involve incorporating the device into a smartwatch system to increase device wearability and reduce size.

References

[1] P. J. Ostergaard, M. A. Meyer, and B. E. Earp, "Non-operative treatment of carpal tunnel syndrome," *Current reviews in musculoskeletal medicine*, vol. 13, no. 2, pp. 141–147, 2020.

[2] Carpal tunnel syndrome. Mayo Clinic. [Online]. Available: https://www.mayoclinic.org/diseases-conditions/carpal-tunnel-syndrome/symptoms-causes/syc-20355603

[3] R. Herbert, F. Gerr, and J. Dropkin, "Clinical evaluation and management of work-related carpal tunnel syndrome," *American journal of industrial medicine*, vol. 37, no. 1, pp. 62–74, 2000.

[4] B. A. Silverstein, L. J. Fine, and T. J. Armstrong, "Occupational factors and carpal tunnel syndrome," *American journal of industrial medicine*, vol. 11, no. 3, pp. 343–358, 1987.

[5] A. K. Mohamed and B. Sathiyasekaran, "Computer professionals and carpal tunnel syndrome (cts)," *International Journal of Occupational Safety and Ergonomics*, vol. 12, no. 3, pp. 319–325, 2006.

[6] J. H. Andersen, J. F. Thomsen, E. Overgaard, C. F. Lassen, L. P. A. Brandt, I. Vilstrup, A. I. Kryger, and S. Mikkelsen, "Computer use and carpal tunnel syndrome: a 1-year follow-up study," *Jama*, vol. 289, no. 22, pp. 2963–2969, 2003.

[7] V. Jagga, A. Lehri, S. Verma *et al.*, "Occupation and its association with carpal tunnel syndrome-a review," *Journal of Exercise Science and Physiotherapy*, vol. 7, no. 2, p. 68, 2011.

[8] M. T. Altinok, O. Baysal, H. M. Karakas, and A. K. Firat, "Sonographic evaluation of the carpal tunnel after provocative exercises," *Journal of ultrasound in medicine*, vol. 23, no. 10, pp. 1301–1306, 2004.

[9] M. Ghasemi-Rad, E. Nosair, A. Vegh, A. Mohammadi, A. Akkad, E. Lesha, M. H. Mohammadi, D. Sayed, A. Davarian, T. Maleki-Miyandoab *et al.*, "A handy review of carpal tunnel syndrome: From anatomy to diagnosis and treatment," *World journal of radiology*, vol. 6, no. 6, p. 284, 2014.

[10] M. Van Suchtelen, S. J. Becker, J. S. Gruber, and D. Ring, "Progression of carpal tunnel syndrome according to electrodiagnostic testing in nonoperatively treated patients," *Archives of Bone and Joint Surgery*, vol. 2, no. 3, p. 185, 2014.

[11] F. Ortiz-Corredor, F. Enríquez, J. Díaz-Ruíz, and N. Calambas, "Natural evolution of carpal tunnel syndrome in untreated patients," *Clinical neurophysiology*, vol. 119, no. 6, pp. 1373–1378, 2008.

[12] H. Carlson, A. Colbert, J. Frydl, E. Arnall, M. Elliot, and N. Carlson, "Current options for nonsurgical management of carpal tunnel syndrome," *International journal of clinical rheumatology*, vol. 5, no. 1, p. 129, 2010.

[13] "Carpal tunnel syndrome fact sheet," NIH Publication No. 20-NS-4898, National Institute of Neurological Disorders and Stroke, 2020.

[14] P. J. Keir, J. M. Bach, M. Hudes, and D. M. Rempel, "Guidelines for wrist posture based on carpal tunnel pressure thresholds," *Human factors*, vol. 49, no. 1, pp. 88–99, 2007.

[15] S. Park, Y. Jung, and J. Bae, "A tele-operation interface with a motion capture system and a haptic glove," in *2016 13th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*. IEEE, 2016, pp. 544–549.

[16] P. Lu and M. Huenerfauth, "Accessible motion-capture glove calibration protocol for recording sign language data from deaf subjects," in *Proceedings of the 11th international ACM SIGACCESS conference on Computers and accessibility*, 2009, pp. 83–90.

[17] P. Polygerinos, K. C. Galloway, E. Savage, M. Herman, K. O'Donnell, and C. J. Walsh, "Soft robotic glove for hand rehabilitation and task specific training," in *2015 IEEE international conference on robotics and automation (ICRA)*. IEEE, 2015, pp. 2913–2919.

[18] M. Nishiyama and K. Watanabe, "Wearable sensing glove with embedded hetero-core fiber-optic nerves for unconstrained hand motion capture," *IEEE Transactions on Instrumentation and Measurement*, vol. 58, no. 12, pp. 3995–4000, 2009.

[19] J. C. Yeo, C. Lee, Z. Wang, and C. T. Lim, "Tactile sensorized glove for force and motion sensing," in *2016 IEEE SENSORS*. IEEE, 2016, pp. 1–3.

[20] Cyberglove systems. [Online]. Available: http://www.cyberglovesystems.com/

[21] J. Henderson, J. Condell, J. Connolly, D. Kelly, and K. Curran, "Review of wearable sensor-based health monitoring glove devices for rheumatoid arthritis," *Sensors*, vol. 21, no. 5, p. 1576, 2021.

[22] F. M. Sánchez-Margallo, F. J. Pérez-Duarte, J. A. Sánchez-Margallo, M. Lucas-Hernández, A. M. Matos-Azevedo, and I. Díaz-Güemes, "Application of a motion capture data glove for hand and wrist ergonomic analysis during laparoscopy," *Minimally Invasive Therapy & Allied Technologies*, vol. 23, no. 6, pp. 350–356, 2014.

[23] H. Beyer and K. Holtzblatt, "Contextual design," *interactions*, vol. 6, no. 1, pp. 32–42, 1999.

[24] A. Presazzi, C. Bortolotto, M. Zacchino, L. Madonia, and F. Draghi, "Carpal tunnel: Normal anatomy, anatomical variants and ultrasound technique," *Journal of ultrasound*, vol. 14, no. 1, pp. 40–46, 2011.

[25] *MyoWare Muscle Sensor (AT-04-001) Datasheet*, Advancer Technologies, 2015-2016. [Online]. Available: https://github.com/AdvancerTechnologies/MyoWare_MuscleSensor/blob/master/Documents/AT-04-001.pdf

[26] Considerations for the design and execution of medical device trials. Premier Research. [Online]. Available: https://premier-research.com/perspectivesmedical-devices-vs-drug-trials/

Appendix A
Investigational Device Details

A. *Figures*

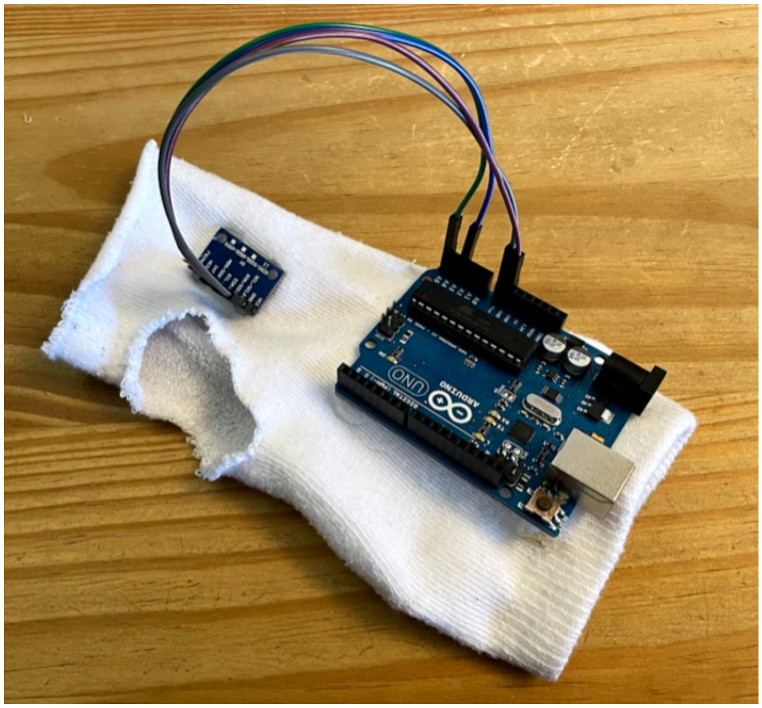


Fig. A1. Prototype IMU testbed for developing wrist-overuse detection algorithm and measuring preliminary wrist angle data.

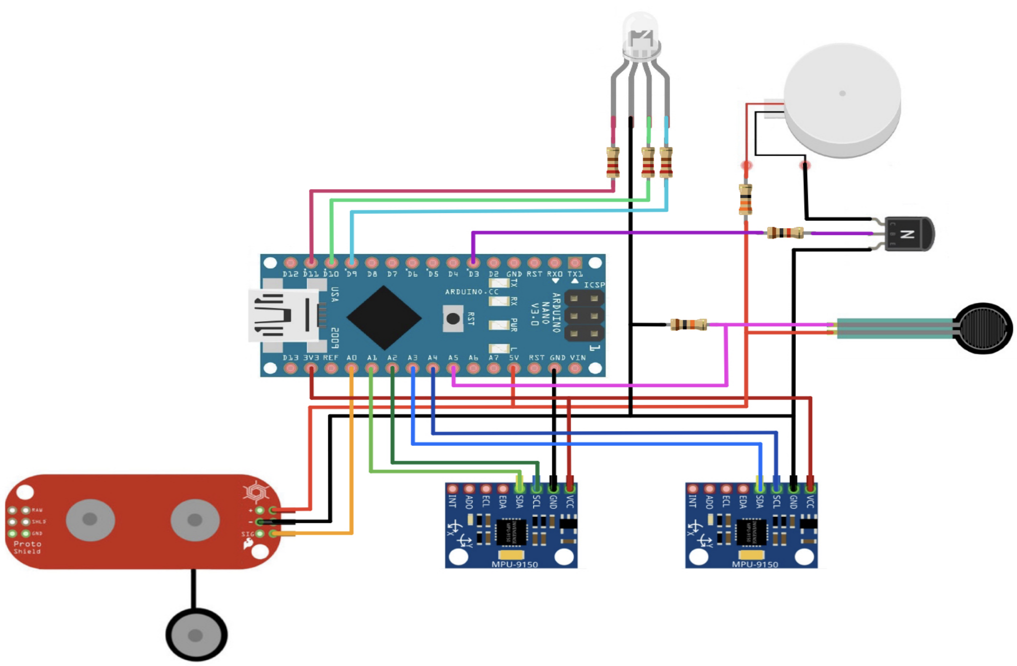


Fig. A2. Wiring diagram for prototype setup, including Arduino Nano, MyoWare Muscle Sensor, two MPU-9250 9-Axis IMUs, an RGB LED with three 220Ω resistors, a vibration motor with a NPN Transistor, as well as 1kΩ and 33Ω resistors, and a FSR with a 10kΩ resistor

B. Arduino Code

```
// Wenny Miao, Kellen O' Rourke
// ME 179 Carpal Tunnel Over-Use Warning Glove Arduino Code
// May 4, 2021

//IMU
#include "MPU9250.h"
MPU9250 mpu;
int rollVal = 0; //Value of output from IMU
int rollI = 0; //Integral of wrist angle from IMU with respect to time
int rollThresh = 30; //Value at which wrist angle is detected to be too high
int rollMax = 80;
float IMUscore = 0.5; //Scoring Constant for IMU
int maxRoll = 80; // Maximum roll for IMU

//Muscle Sensor
#define muscPin A0
int muscVal = 0; //Value of output from muscle sensor
float muscI = 0; //Integral of muscle sensor value with respect to time
int muscThresh = 200; //Value at which muscle activity is detected to be too high
float muscScore = 0.5; //Scoring Constant for Muscle Sensor
float maxMusc = 1023; // Maximum output for Muscle Sensor (observed)

//Time
unsigned long currTime = 0; //Current Time
unsigned long prevFSRTime = 0; //Time at which FSR was last triggered
unsigned long prevAlertTime = 0; //Time at which Alert was last triggered
unsigned long prevSensorTime = 0; //Time sensor readings were last updated
unsigned long sensorUpdateDelay = 1000; //Delay time between sensor readings to reduce size of
    data

//Alert - Buzzer and RGB LED
bool alertTriggered = false;
unsigned long alertTimeThresh = 10; //Each alert triggers for at least 30 seconds
float overUseScore = 0; //Weighted sum of integrals of wrist angle and muscle data
float scoreThresh = 10; //Threshold for overuse trigger

#define buzzerPin 3
const int songLength = 6;
char notes[] = "c␣c␣c␣";
int beats[] = {2, 2, 2, 2, 2, 2};
int tempo = 113;

#define redPin 11
#define greenPin 10
#define bluePin 9

//FSR
#define fsrPin A5
int fsrValue = 0;
int fsrPressed = false;
int fsrThresh = 100;
int FSRTimeThresh = 5000; // Time delay  before new pain reading recognized

void setup() {
  Serial.begin(115200);
  //Wire.begin();

  //Alert Output Initialization
  pinMode(buzzerPin, OUTPUT);
  pinMode(redPin, OUTPUT);
  pinMode(greenPin, OUTPUT);
  pinMode(bluePin, OUTPUT);

    //IMU Setup
```

```
    delay(1000);
    if (!mpu.setup(0x68)) {
      while(1){
        Serial.println("MPU connection failed.");
        delay (5000);
      }
    }
}

void loop() {
  currTime = millis();

  //Update Sensors
  if (currTime > prevSensorTime + sensorUpdateDelay) {
    prevSensorTime = currTime;
        if (mpu.update()){
          // Temporary code to account for lack of second IMU, assumes wrist flat on table
          rollVal = mpu.getRoll();
          if (rollI >= 0) {
            if (rollVal > rollThresh && rollVal < rollMax) {
              rollI = rollI + rollVal;
            }
            else if (rollVal > 0 && rollVal < rollThresh){
              rollI = rollI - rollThresh;
              if (rollI < 0){rollI = 0;}
            }
            else {rollI = rollI;}
          }
        }
    muscVal = analogRead(muscPin);
    if (muscI >= 0) {
      if (muscVal > muscThresh) {
        muscI = muscI + muscVal;
      }
      else if (muscVal < muscThresh) {
        muscI = muscI - muscVal;
        if (muscI < 0) {
          muscI = 0;
        }
      }
      else {
        muscI = muscI;
      }
    }

    //Alert if Above Thresholds, Stop Alert if Below Threshold
    overUseScore = muscScore * muscI * (1/maxMusc) + IMUscore * rollI * (1/maxRoll); //Weighted
         sum of integrals, normalized for max value

    if (overUseScore > scoreThresh && alertTriggered == false) {
      alertTriggered = true;
      playsong(); //Play song, will be replaced with vibration motor in actual device
      prevAlertTime == currTime;
    }
    else if (overUseScore < scoreThresh && alertTriggered == true &&  currTime - prevAlertTime
        > alertTimeThresh) {
      alertTriggered = false;
    }

    // Change LED Colors based on Alert State
    if (alertTriggered == true) {
      RGB_color(255, 0, 0);
    }
    else {
      RGB_color(0, 255, 0);
```

```
    }

    // Decrease Thresholds if User Indicates Pain
    fsrValue = analogRead(fsrPin);

    if (fsrValue > fsrThresh && fsrPressed == false && currTime - prevFSRTime > FSRTimeThresh)
        {
      scoreThresh = scoreThresh - 1;
      prevFSRTime = currTime;
      fsrPressed = true;
    }
    else if (fsrValue < fsrThresh && fsrPressed == true) {
      fsrPressed == false;
    }

    // Increase Thresholds if No Pain Alerted for Over a Day
    if (currTime - prevFSRTime > 8.64e7) {
      scoreThresh = scoreThresh + 1;
      prevFSRTime = currTime;
    }

    // Account for resets in Millisecond Timer
    if (currTime < prevFSRTime || currTime < prevAlertTime) {
      prevFSRTime = 0;
      prevAlertTime = 0;
    }
  }
}

// RGB LED Functions
void RGB_color(int red_light_value, int green_light_value, int blue_light_value)
{
  analogWrite(redPin, red_light_value);
  analogWrite(greenPin, green_light_value);
  analogWrite(bluePin, blue_light_value);
}

//Buzzer Functions
void playsong()
{
  int i, duration;

  for (i = 0; i < songLength; i++) // step through the song arrays
  {
    duration = beats[i] * tempo;  // length of note/rest in ms

    if (notes[i] == '␣')          // is this a rest?
    {
      delay(duration);            // then pause for a moment
    }
    else                          // otherwise, play the note
    {
      tone(buzzerPin, frequency(notes[i]), duration);
      delay(duration);            // wait for tone to finish
    }
    delay(tempo / 10);            // brief pause between notes
  }
}

int frequency(char note)
{
  // This function takes a note character (a-g), and returns the
  // corresponding frequency in Hz for the tone() function.

  int i;
```

```
  const int numNotes = 3;  // number of notes we're storing

  char names[] = { 'c', 'd', 'e', 'f', 'g', 'a', 'b', 'C' };
  int frequencies[] = {262, 294, 330, 349, 392, 440, 494, 523};

  // Now we'll search through the letters in the array, and if
  // we find it, we'll return the frequency for that note.

  for (i = 0; i < numNotes; i++)  // Step through the notes
  {
    if (names[i] == note)         // Is this the one?
    {
      return (frequencies[i]);    // Yes! Return the frequency
    }
  }
  return (0); // We looked through everything and didn't find it,
  // but we still need to return a value, so return 0.
}
```

Appendix B
Collecting and Analyzing Interview Data

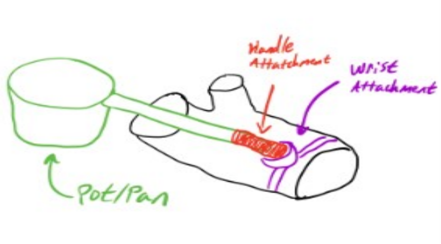
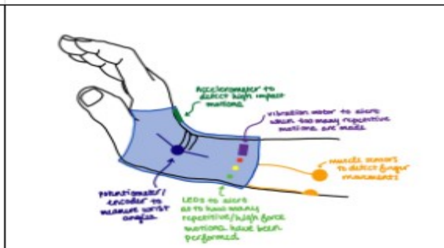
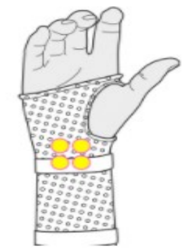
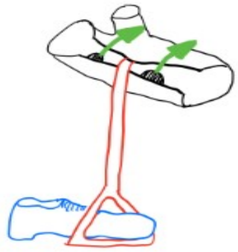
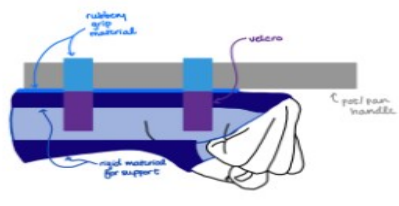
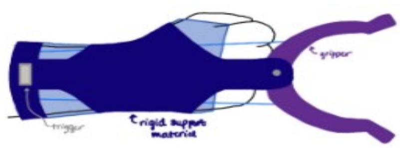
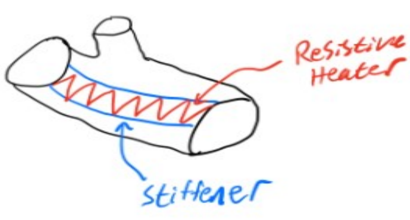
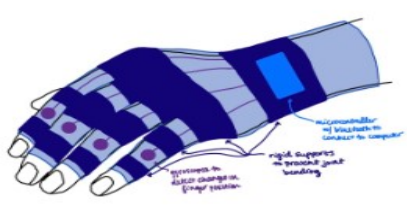
A. *User Needs Chart*

Question/Prompt	Customer Statement	Interpreted Need
General Activities that Cause Hand and/or Wrist Pain	"I like to knit and crochet, so that's a kind of hand manipulation faced hobby and I think it was the repetitive motion and the force that was required that caused stress in my wrist"	Device prevents repetitive motions and high stress in wrist
	(Demonstrating using crochet hook) "I would be hodlding it like a pencil, and poke a hole in the thing then pull it out using this wrist motion, so it's a lot of wrist snapping going on"	Device prevents fast, "snapping" motions of the wrist
Diagnosis	"There were small pangs of pain in the wrist that I overlooked" (in weeks before overdoing it and getting bad pain)	Device helps keep track of wrist pain/pressure levels
	"Completely overlooked the kinds of pain I had in the wrist once in a while, didn't really think much of it"	Device helps keep track of wrist pain/pressure levels
	(Crocheted a lot one day) "I really felt pain, but I just kept going because I didn't know that I needed to stop"	Device alerts when a certain pain/pressure threshold is exceeded
Treatment	"I think it was making sure I wasn't overstraining my wrist, than any treatment I got (accupuncture)"	Device prevents overstraining of wrist
	(Didn't go to a doctor) "It was half because I thought I could wait it out, and didn't feel like I could go to a doctor in the middle of COVID"	Device helps determine when doctor visit is necessary
Uncomfortable Daily Devices/Tools	"When I had the bad carpal tunnel, using the keyboard on my laptop directly was a little hard. On the other hand, I tried a keyboard with a slope that allowed my wrist to rest, which felt a lot better"	Device allows wrist to rest in stretched position when typing
	"I was typing with a few fingers at a time, instead of my whole hand (demonstrated typing with only pointer finger), it was very slow"	Device allows user to type more quickly
	"Anything that required any coordinated motion of the hand was kind of painful, especially any bending movement... if I were to type on a sloped keyboard my hand would be stretched out a bit more (better)"	Device prevents bending movements of wrist
	"Using my phone was pretty hard since I would use my right hand and my thumb could not extend (in the brace), and (without the brace) my wrist would be stretched... I would put the phone down and tap with one finger"	Device allows user to hold and manipulate smartphone
	"I feel a little worried that I'm stressing out my wrist by moving pots... feels more straining doing it now"	Device allows user to hold and support heavy objects
	"Even a water bottle, if it were too heavy I would feel pain in the wrist, I would try to keep using my left hand instead... again, I think it's the angle"	Device allows user to hold and support heavy objects (provides better angle?)
	"Any time I tried them (ergonomic keyboards) to see which one is most comfortable, nothing felt comfortable enough."	Computer interface that actually does feel comfortable to use
	"I used to grab like 4 or 5 plates at one time. Now I have to take maybe 2 at a time."	Ability to comfortably lift more weight during household/office tasks
	(while demostrating how she holds a pan) "When I hold something right here the pain shoots all the way up here, and my thumb hurts."	Reduce thumb force required for holding cantilever handles (like a pan)
	"It is really the position of the handle that makes it challenging to hold."	Ergonomic hand position for cantilever handles (like a pan)
	"picking up a little item, like holding a pen, even at one point was difficult for me."	Make manipulating smaller items (pen, spoon, etc.) more comfortable and reliable
	Daily activities such as washing dishes, holding tools became difficult.	Device allows daily activities such as washing dishes and holding tools
	(mouse pad) "Without that little bump, it was really really difficult for me to hold my hand in that position."	Need support that encourages proper wrist posture while using mouse
Current Assistive Devices	(Arm Sling) "That would help me not use my right hand, since it's my dominant hand. It would help me start with my left hand instead of going straight to my right"	Device prevents use of affected hand
	(Arm Sling) "It was annoying to put this on since I couldn't get it on unless I had my arm in first, then put my head through"	Device is easy to put on and use
	(Wrist Brace) "Sometimes I would have it on when I slept, but that wouldn't be very good for blood circulation"	Device allows for good blood circulation to hand
	(Wrist Brace) "Sometimes it pushes against my forearm, which is kind of annoying but not a big deal"	Device feels comfortable and does not dig into arm
	(Wrist Brace) "Did help me secure my wrist, but because my fingers were still exposed I would try to use them, which would still cause wrist pain"	Device prevents finger motion
	(Wrist Brace) "It can be difficult to slide under clothes"	Device is slim enough to fit under clothes
	(Wrist Brace) "Some times I would sweat inside, and I would have to try to leave it off for a bit"	Device is breathable and not too hot
	(soft brace) "In the beginning it helped releasing the tension, but as the pain progressed it wasn't as helpful."	Device is stiff enough to release tension even as wrist pain evolves
	"I cannot cook, I cannot work, I cannot do daily activites, I just have to sit and rest with that thing on."	Device doesn't prevent daily activites (cooking/working)
	The firm brace gives a better stability and immobilizes the hand in a certain position. However, the way they made it is hard to put it on and off.	Device needs to be easy to put on and off.
	To buckle the firm device right, you need someone's assistance	Device needs to be able to be put on by the user
	The soft brace is too soft and it does not fully serve the purpose as much.	Device is firm enough to give a good support.
	(soft brace) " I like that it's so easy to put on and off... its like a sock."	Device goes on and off with one hand and without outside help
	"I think it would be helpful if you could have a kind that can get warm"	Device controls wrist temperature
	"It's not really about the look for me, its about how effective it is"	Device does not sacrifice functionality for aesthetics

B. Hierarchical List of Needs

Primary		Secondary	
Need	**Priority**	**Need**	**Priority**
Ease of Use	1	Device is easy to use	1
		Device goes on and off with one hand and without outside help	2
Immobilization/Posture	2	Device prevents overstraining of wrist	1
		Device is firm enough to give a good support.	2
		Device prevents bending movements of wrist	
		Device is stiff enough to release tension even as wrist pain evolves	
		Device prevents repetitive motions and high stress in wrist	3
		Device prevents fast, "snapping" motions of the wrist	
		Need support that encourages proper wrist posture while using mouse	4
		Device allows wrist to rest in stretched position when typing	5
		Device limits finger motion	6
		Device prevents use of affected hand	7
Stabilization/Lifting	3	Ability to comfortably lift more weight during household/office tasks	1
		Device allows user to hold and support heavy objects (provides better angle?)	2
		Reduce thumb force required for holding cantilever handles (like a pan)	3
		Ergonomic hand position for cantilever handles (like a pan)	4
Manipulation	4	Device doesn't prevent daily activites (cooking/working)	1
		Make manipulating smaller items (pen, spoon, etc.) more comfortable and reliable	2
		Device allows user to type more quickly	3
		Device allows user to hold and manipulate smartphone	4
Comfort	5	Device allows for good blood circulation to hand	1
		Device feels comfortable and does not dig into arm	2
		Device is breathable and not too hot	3
		Computer interface that actually does feel comfortable to use	4
Diagnostics/Treatment	6	Device helps keep track of wrist pain/pressure levels	1
		Device alerts when a certain pain/pressure threshold is exceeded	2
		Device controls wrist temperature	3
		Device helps determine when doctor visit is necessary	4
Form/Aesthetics	7	Device is slim enough to fit under clothes	1
		Device does not sacrifice functionality for aesthetics	2

C. ***Brainstorming Summary***

		
Brace: Handle Attachment - Ball/socket system for supporting cantilever handles - Moment load distributed between hand and forarm	**Movement Detection Glove** - Detects finger, wrist, and hand motions to warn the user when too many repetitive/snapping motions are performed	**Moveable Spheres** -Heat controlled and rotating spheres that will warm the area assocaited with CT and massage at the same time.
		
Brace: Foot Support for Donning - Enables 1 handed donning by using the foot as a support to resist hand force	**Handle Attachment Brace** - Velcro straps to hold and lift pan/pot hand, support weight with forearm rather than wrist	**The Right Shape** -To make the brace cut in a way that it maximizes support and movement capabilities.
		
Brace: Variable Stiffness - Mechanism to vary stiffness - Can make brace soft for donning - Can adjust stiffness for varying pain levels	**Gripper Brace** - Gripper attached to brace to be able to hold objects without using hands, and support weight using forearm	
		
Brace: Resistive Heater - Can control wrist temperature to reduce wrist pain	**Keyboard Glove** - Detect small finger movements (up, down, left, right) and map to common keys on keyboard (16 possible total)	

D. Idea Selection

Option \ Criteria	Ease of Use 2	Prevention 2	Novelty 2	Immobilization 2	Manipulation 2	Lifting 1	Comfort 1	Fit with Class 1	Cost/Complexity 1	Final Score
Brace: Standard	0	0	0	0	0	0	0	0	0	0
Brace: Handle Attachment	-2	0	1	1	0	1	1	1	-1	2
Brace: Foot Support for Donning	1	0	1	0	0	0	0	1	-1	4
Brace: Variable Stiffness	1	0	1	1	0	0	1	1	-3	5
Brace: Resistive Heater	-2	0	1	0	0	0	2	1	-3	-2
Movement Detection Glove	-3	3	3	-1	1	-1	0	3	-3	5
Handle Attachment Brace	-1	0	1	1	0	1	1	1	-1	4
Gripper Brace	-2	0	1	0	2	1	1	4	-3	5
Keyboard Glove	-4	0	2	1	2	0	2	3	-4	3
Moveable Spheres	-2	0	2	0	0	0	3	3	-3	3
The Right Shape	0	0	0	-1	2	0	1	1	0	4

* Standard Wrist Brace is baseline, +/- system comparing option to baseline, weights are shown under criteria

We decided to further develop the ”Movement Detection Glove”, which has tied for highest score in our selection matrix. Based on our interviews and reading, we believe it addresses a need few existing devices focus on, and presents an opportunity for prevention of disease progression itself, rather than just symptom relief. It includes a variety of sensors to help detect aspects such as hand motions and pain, which could be used to warn the user before too many repetitive motions are performed, reducing risk of condition progression. Data gathered may also be useful to better understand the pathophysiology of the condition and the efficacy of various treatment options.