Haptic feedback thumb exoskeleton to reduce hypersensitivity and improve pressure feedback

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Abstract

The development of neuroma (sensitive nerve bundles) is a common effect of peripheral nerve injuries. These injuries can lead to prolonged periods of hypersensitivity in the affected area and loss of tactile and proprioceptive feedback. As part of this study, we interviewed a cardiologist with a severed and reattached nerve on the volar and radial side of this thumb. Based on the needs identified from the interview, we propose an electromechanical device that helps in providing protection to the affected area by transferring the mechanical load to other non-sensitive regions. The device is also equipped with a force-sensitive resistor (FSR) sensor that helps in providing haptic pressure feedback when there is contact on the affected area via a vibration motor attached to the wrist. To test the efficacy of our device a comparative study is proposed. The device presents a viable solution and is able to address an existing gap for a specific use case.

I. Introduction

Injuries to the hand are very common; 7 to 37/1000 inhabitants/year in Europe have hand injuries, and 50 percent of them are fractures [1]. Out of these around 0.14/1000 inhabitants/year have peripheral nerve injuries [1]. Even though this number is not huge, nerve injuries can be challenging to treat. Nerves act as sensing mechanisms that help interact with our environment by giving tactile and proprioceptive feedback. These can be damaged due to penetrating trauma to the hand that can result in fractured bones or severed nerves. Severed nerves can lead to hypersensitivity in the affected area, which can cause pain, tingling sensations, numbness, and increased response to touch contact. Damaged nerves can also lead to a loss in feedback mechanisms, leading to difficulty in grasping things and clumsy movements. Severed nerves are, in most cases, surgically repaired by joining them together and putting a splint at the place of injury. They are then allowed to heal naturally by regeneration, hoping for normal functioning within a limited period of time [2]. Our project tries to tackle problems faced due to injuries to nerves in the hand which can lead to increased hypersensitivity in the region and reduced pressure feedback.

A. Background

Injuries caused to peripheral nerves in the hand are generally treated using desensitization techniques. Desensitization techniques use physiotherapy, a range of motion and strengthening exercises, and also vibration therapy for quick recovery [3]. Desensitization in the early phase of the injury could include dressing up the wound area to reduce edema and control pain [4]. During the later phases of the injury, a range of motion and strengthening exercises that help in sensory re-education are prescribed [4]. Protection gloves available in the market are also used for protecting the thumb and in rehabilitation activities for exercising.

Exoskeleton rehabilitation devices, biologically inspired soft-robotic devices and haptic feedback devices are also some solutions that focus on increasing the range of motion and providing haptic feedback [5]. These techniques are mostly used to achieve better overall motion including flexion and extension of fingers and wrist and provide touch feedback.

More sophisticated robotic exoskeletons have also been researched and studied as a solution. A study talks about a 2-DOF exoskeleton that provides a range of motion required for the thumb [3] [6]. Soft robotic thumb exoskeletons that are biologically inspired are also researched and studied in academia as full rehabilitation devices [5]. They are used to restore thumb motor functioning caused in patients due to neurologically dysfunctions [5]. Most of these exoskeletons are not prescribed for hypersensitivity shielding and that is where our current device fills in the gap.

Haptic feedback systems are used extensively in robotic systems for providing touch and pressure feedback. These are mainly electromechanical systems that rely on a sensor such as piezoelectric, electroactive polymers, and electrostatic to generate vibration through mechanical actuators [7] [8]. Our device uses a force-sensing resistor (FSR) to detect how much pressure is being applied. The pressure detected is then transferred to a vibration motor to notify the user.

B. Overview

Section II of the report presents an interview case study of a need-knower who had serious damage to his hand during an accident with a car. An in-depth analysis of the interview and the needs interpreted are presented in this section. In Section III-A we propose an electromechanical device that helps protect the thumb against hypersensitivity issues and also provides pressure feedback to its user. We hypothesize that a device that both guards the thumb and provides haptic feedback upon contact will result in a more comfortable experience when interacting with different objects and environments and increase the speed of functioning. In Section III-B, we propose a set of test methods to test our hypothesis. We propose testing with the mechanical shielding and the haptic system turned on and off.

II. Interview case study

We contacted an electrocardiologist at UCSF and conducted a 60-minute interview to determine his needs pertaining to a hand injury he suffered in recent times. This interview was conducted remotely via Zoom with audio, video, and transcript recording. Our team of three interviewers consisted of 2 note takers and one main interviewer asking questions with support as needed. In his line of work, the need-knower performs surgeries related to the implantation and removal of pacemakers and defibrillators. In the interview, the need-knower confirmed many of our initial findings and further revealed additional details about his condition that would greatly impact the design choices of our project. He suffered a dominant hand thumb injury about a year and a half ago that resulted in a badly fractured thumb and extensive nerve damage in that area. Three major areas where our need-knower identified problems were restricted flexion motion of the DIP (Distal Interphalangeal) joint of the dominant hand thumb, loss of temperature and precision sensing on the radial sides of the thumb, and development of neuroma (sensitive nerve bundle because of nerve reattachment) covering almost half of the thumb. The need-knower has undergone physical therapy exercises to regain DIP motion since his initial injury and recovery but stated that his flexion ability has not improved much since the initial injury. The hypersensitivity, a lack of flexibility, and inability to feel caused a lot of challenges in carrying out day-to-day activities like opening a jar, writing, buttoning up a shirt, playing golf, scrolling on the phone, or pressing buttons on the remote. He also mentioned that while performing surgeries and procedures, it is difficult for him to pick up small objects and position them precisely in relation to other objects.

While he was very well adapted to the cardiac catheterization procedure, he faced difficulty with fine motor movements while working with a guide wire (less than 1 mm), where he had to observe if he had a good grasp because of a lack of grip feedback (he explained it as “I have to just pick up slower and use eyes to see that grasp”) or the actions that required thumb pressure like injecting the syringe. The need-knower said this pain becomes more noticeable when he does other things outside of work, such as cooking, writing, or when playing sports. Throughout our interview, the need-knower emphasized hypersensitivity being much of an obstacle and that he had to be careful not to rub his thumb against surfaces while performing different activities. He quoted “Just touching (the radial side of my thumb) is uncomfortable and it’s tingly like an electric shock.” This led us to investigate a need that would be significant enough to improve the quality of life for our need-knower.

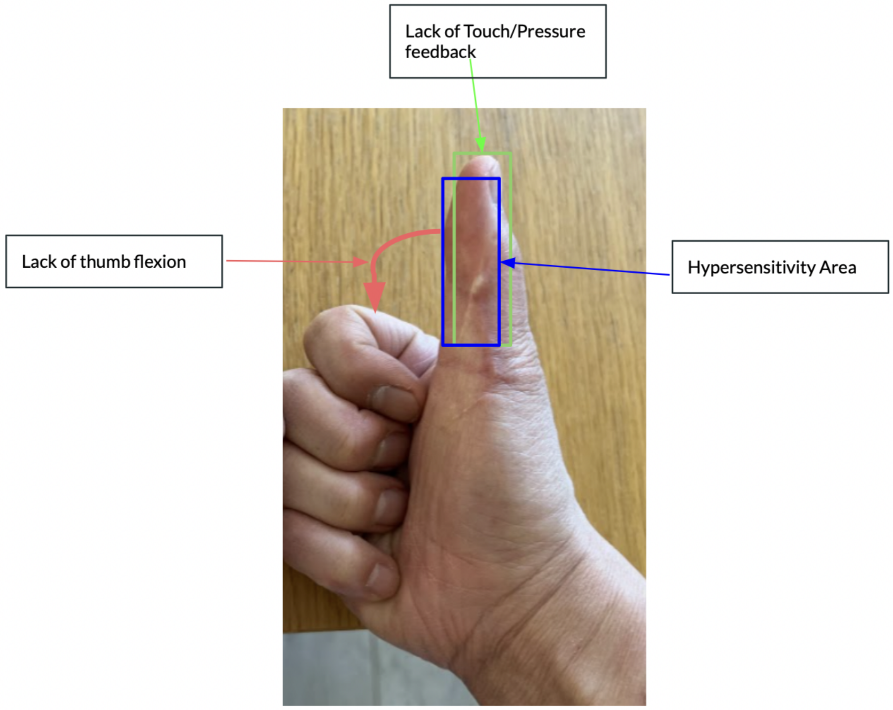

Fig. 1: Primary needs identified

Prompt/Theme	**Interview statement**	**Interpreted need**
Mundane activities	"Little things like opening a jar is uncomfortable." "One of the things that affect me a lot is just writing." "Cooking is something I struggle with. I cannot sense temperature on the thumb tip."	Values independence.
	"Buttoning up shirts and pushing the button through is actually very hard for me." "I hold the phone more often, with the left hand and use other fingers to scroll the phone."	To increase the range of motion in DIP (Distal Interphalangeal) joint. User is adaptive.
Performing Surgeries	"Using the assistive device was a hassle, need to put it on, take off, again put it on."	Values comfort.
	"The sensations are not as good. I Have to look at my fingers to notice whether I have picked the catheter tubes or not."	Believes in efficiency.
Subconscious Actions	"Just touching (the radial side of my thumb) is uncomfortable and it's tingly like an electric shock."	Protection against rubbing of the hypersensitive part.
	"I have to just pick up slower and use eyes to see that grasp."	Likes doing activities at a fast pace.

TABLE I: Identified need from the primary interview

III. Proposed Device & Test Methods

A. Proposed Device

Our proposed device is a protective thumb cover that prevents unpleasant pressure/touch skin sensations on the volar and radial sides of the thumb while still providing touch/pressure feedback to the user by sensing and transferring sensation to non-hypersensitive regions of the hand. Our prototype consisted of a low-profile, skeletonized snap-fit thumb cage and sensing circuit comprised of an Adafruit Gemma M0, FSR402 force sensitive resistor, and vibration motor. For the final prototype thumb cage, our group decided to use a Formlabs resin printer and "Durable" resin for its smooth finish and tough properties. While we considered printing the connecting beams of the cage out of flexible material using a PolyJet process to allow for flexion of the thumb, we ultimately decided against it as the soft nature of the material may allow it to compress against the skin and our need-knower does not have the ability to flex their thumb. Rewatching the surgery footage to see how exactly our need-knower uses his hands, we decided to place the FSR on the volar tip of the thumb cage as that is the region he tends to use most when performing precise grabbing motions. Finally, we placed the vibration motor and microcontroller on the dorsal side of the wrist to ensure the force feedback is distinct enough from other sensations around the hand and to avoid impeding the dexterity of other digits. Design files for the custom 3D-printed thumb cover can be found in **Appendix A**.

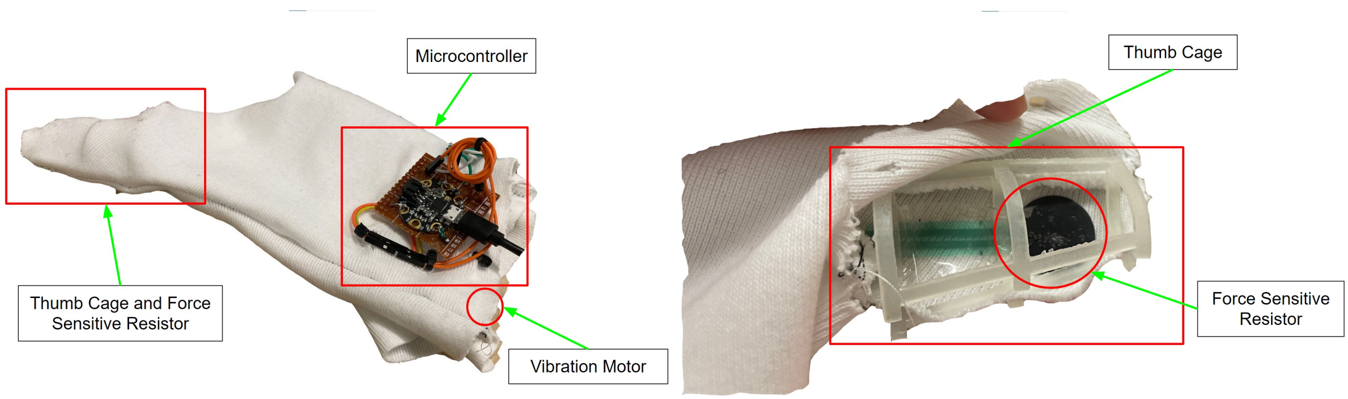

Fig. 2: Device Components

B. Test Methods

We split our testing procedures into Section A and Section B with Section A focused on calibrating the device and Section B diving into a comparison between using the device vs. not using the device.

For Section A, separate tests were run on the hardware and electronic portions of the device to find the best combination of design and feedback.

In order to test the hypersensitivity protection element of our proposed device, we devised a rubric for human test subjects to use in grading our prototype's protection ability, comfort, secureness of fit, and dexterity on scales of 1-5. Each of these categories was rated after performing a series of common hand tasks (writing, picking up various objects, opening doors, typing, smartphone usage) and more niche tasks specific to our need-knower (threading a tube through a narrow opening, putting on gloves). Using this rubric, we iterated and optimized the thumb cover's shape and material in response to test subject feedback.

To test the touch/pressure feedback portion of our device, we attached an FSR to the volar tip of the protective thumb cover and adhered a small vibration motor to the dorsal side of the user's hand/wrist. Another similar rubric is planned to acquire user feedback on ideal vibration motor strength as well as vibration motor placement.

Moving onto Section B, we conducted a number of timed subject trials with/without the device and with/without force feedback. During these tasks, subjects were observed by researchers and asked to provide comments and feedback on their experiences after the timed trials. Test subjects performed tasks such as picking up a pen from a table, grasping a water bottle, and threading a wire into a tube.

We expected that subjects would see an improvement in speed when performing tasks and increased comfort from the shielding of the volar thumb region. During internal group testing, we did experience benefits from additional force feedback but struggled to optimize further since our group had normative hand function instead of the need-knower's specific condition.

We used these protocols with internal group testing to develop our first prototype and intend to submit these procedures for review through the Internal Review Board for Protection of Human Subjects in accordance with CITI training Group 1: Biomedical Research Investigators completed on 4/4/23 to conduct wider human subject testing.

IV. Intellectual Merit

While several devices exist to reduce the hypersensitivity of the skin or provide tactile feedback in response to senseless areas, few offer both at the same time and none accomplish both of these feats at an affordable price. Our device aims to tackle these challenges differently from existing desensitization therapy techniques by utilizing a protective cage and incorporating haptic feedback such that the user is protected from unpleasant pressure contact but still gains the benefits of touch feedback. Our device differs from existing products such as gloves through its “air bubble” approach to protection ensuring that pressure is not exerted on sensitive areas and instead rerouted to normative areas.

While our product incorporates basic pressure force feedback, we do not currently have any systems for measuring shear forces or pinpointing where the FSR force is exerted. Future studies with this “selective sensitivity” approach would likely investigate alternative force sensors and motors or possible purely mechanical connections to transmit force to normative areas.

The above-described device and study could be a potential solution for reducing hypersensitivity, aiding in recovery, and maintaining normative daily functioning for a user. Based on our literature study and exploration, we could not find many solutions that target our need-knower’s specific issue. The major solution that is adopted by users is therapeutic desensitization techniques that are limited in scope and may hinder normative functioning. Thus, our proposed device tries to address an existing gap for a specific use case.

V. Broader Impact

The haptic feedback thumb exoskeleton is designed to reduce hypersensitivity and improve pressure feedback for the need-knower who suffered a thumb injury. It could be professionally challenging for individuals who rely on their hands for work and may experience reduced productivity due to hypersensitivity or loss of pressure feedback. This assistive device can help alleviate these symptoms, allowing the user to perform these activities with greater ease and comfort. This can increase the user’s independence and reduce the need for a caregiver or other forms of assistance allowing the user to perform daily tasks such as writing, typing, and holding objects. The invention is intended to be made open source due to the wide and highly accessible audience. Hand injuries are extremely common worldwide and this device and the technology can be broadly used to alleviate pain and improve work efficiency.

References

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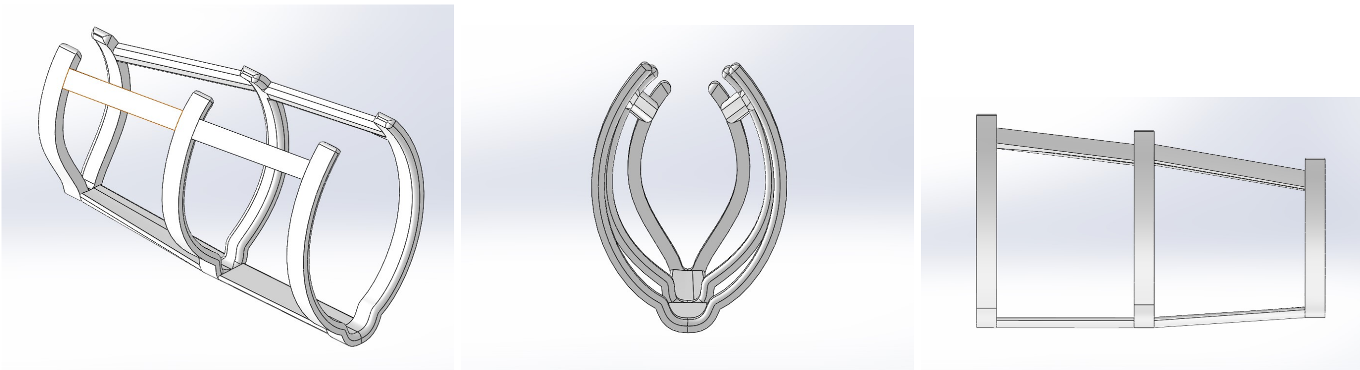
Appendix A
Investigational Device Details



(a) Isometric (b) Front (c) Right

Fig. 3: Thumb Cage

Fig. 4: Cage on cast of Need-knower's Thumb

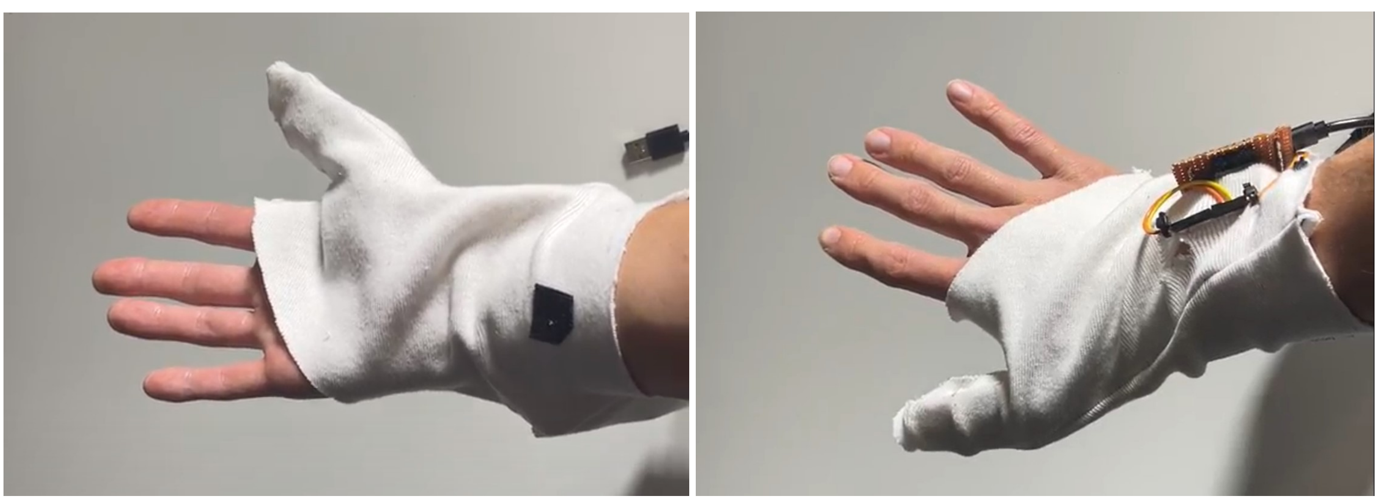


Fig. 5: Device Worn on Hand

Criteria/Needs	Weights (1-5)	Magic Pen	Additional Thumb	Airbag	Rubber Bands/Artificial Tendon	Grip strength feedback	Keyboard
Increase speed of activities	3	3	4	2	2	4	3
Reduce hypersensitivity	4	3	4	5	3	2	3
Grip strength/pressure feedback	4	2	3	1	4	5	1
Range of Motion	3	3	5	3	5	1	2
Comfort	5	3	4	4	4	4	3
Complexity	5	1	1	4	3	4	4
Visually & Tactilely appealing	4	4	3	3	2	3	4
	Total Score	2.64	3.28	2.61	3.28	3.39	2.92

Fig. 6: Weighted matrix used for concept selection

Fig. 7: Brainstorming concept ideas and dot-voting used to narrow down concepts

```
void loop() {
  // put your main code here, to run repeatedly:
  fsrReading = analogRead(fsrAnalogPin);
  Serial.print(fsrReading);
  Serial.print(",");

 static int State = 0;  //initialize the first state as 0
  switch (State) {
    case 0 : //off state
     if (fsrReading <= vibThreshold)   {
     vibPWM = 0;
      digitalfsr = 0;
      Serial.println(digitalfsr);
     analogWrite(VibmotorPin,vibPWM);
     }
     if (fsrReading > vibThreshold)  {
       State = 1;
     }
     break;
   case 1: //vib state
    if (fsrReading > vibThreshold) {
    vibPWM = fsrReading*maxPWM/maxAnalogRead*3;
    Serial.println(vibPWM);
     digitalfsr = 800; //
     Serial.println(digitalfsr);
    analogWrite(VibmotorPin,vibPWM);
    }
    if (fsrReading <= vibThreshold)  {
       State = 0;
     }
     break;

  PrevfsrReading = fsrReading;
}
}
```

Fig. 8: Arduino code for FSR and vibration motor