



VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

FACULTY OF MECHANICS

DEPARTMENT OF BIOMECHANICAL ENGINEERING

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**RESEARCH AND DEVELOPMENT OF TACTILE FEEDBACK (OR
SENSORY FEEDBACK) TECHNOLOGIES FOR APPLICATION IN LIMB
PROSTHESIS**

Master's degree Thesis

Biomedical engineering study programme, state code 6211EX032

Bioengineering study field

Vilnius, 2021

Vilniaus Gedimino technikos universitetas
Mechanikos fakultetas
Biomechanikos inžinerijos katedra

ISBN ISSN
Egz. sk.
Data-.....-.....

Antrosios pakopos studijų **Biomedicininės inžinerijos** programos magistro baigiamasis darbas

Pavadinimas **Taktilinio grįžtamojo ryšio technologijų taikymo galūnių protezavimui kūrimas ir tyrimas**

Autorius **Alicia Menendez Hurtado**

Vadovas **Julius Griškevičius**

Kalba: anglų

Anotacija

Šioje magistro tezėje nagrinėjamas taktilinio grįžtamojo ryšio technologijų taikymas galūnių protezėms siekiant palengvinti jų naudojimą ir pagerinti pacientų gyvenimo kokybę. Išanalizuoti šaltiniai tiriantys rankų, plaštakų, odos anatomiją, amputacijos pagrindus, protezių istoriją, šiuo metu prieinamas protezės su taktiliniu grįžtamuju ryšiu. Atlikti skirtingi eksperimentai siekiant atsakyti klausimus: kokie sensoriai ir aktuatoriai geriausiai tinka šiai paskirčiai, ar pacientai gali atskirti skirtingus vibracijos lygius, ir ar visa sistema gali suprantamai paversti sensoriaus spaudimą į vibraciją. Eksperimentų rezultatai palyginti ir išanalizuoti. Suformuluotos magistro tezės išvados. Tezės apimtis - 44 puslapiai (neskaičiuojant priedų), 32 pavyzdžiai, 3 lentelės, 30 šaltinių.

Prasminiai žodžiai: taktilinis grįžtamasis ryšys, vibracija, galūnės, protezės

Vilnius Gediminas Technical University Faculty of Mechanics Department of Biomechanical Engineering	ISBN ISSN Copies No. Date-.....-.....
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Master Degree Studies Biomedical Engineering study programme Master Graduation Thesis	
Title	Research and Development of Tactile Feedback (or Sensory Feedback) Technologies for Application in Limb Prosthesis
Author	Alicia Menendez Hurtado
Academic supervisor	Julius Griškevičius

Thesis language: English

Annotation In the Master thesis the use of vibrotactile feedback in upper limb prosthesis is researched as a way to add comfort and quality of life to amputees. There is scientific research performed analysing the anatomy of the arm, hand and skin, the basics of amputation, the history of prostheses and the available options of prostheses with tactile feedback. Different experiments are designed to solve which sensors and actuators work best, if continuous vibration levels can be differentiated and if the final system can translate pressure into vibration in an understandable way. The results of the experiments are compared and analyzed numerically. The conclusions of the Master thesis are formulated. Thesis volume - 44 pages of text without appendix, 32 figures, 3 tables, 30 references.

Keywords: Tactile feedback, vibration, upper limb, prosthesis
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INTRODUCTION

Relevance of the problem

Arm and hand prostheses have evolved throughout history adding new features to close the gap between an artificial limb and the original one. The next step to add function to the prosthesis and independence to the user is to add tactile feedback, eliminating the need for visual or auditory cues to use the prostheses. This function also will help amputees feel like their prosthesis is a part of them, rather than a tool that just happens to be attached.

Research goals

The goal of this research is to find a non-invasive and inexpensive way to add tactile feedback to a prosthesis, by using pressure sensors to get the information from the grip and transmitting it to a vibromotor that can reliably send the information to the user, making it possible to differentiate between a gentle touch or light grip and a tight grip on the prosthesis.

Tasks of the research

The goal is to have a proof of concept that a system with barometric sensors and vibromotors can be built and incorporated into a prosthesis to serve as a way to mimic tactile sensation.

The tasks to accomplish this in this particular project are:

- Find a sensor that can register the usual range of pressures that a human hand uses daily
- Find a small actuator that can convey the different pressures from the sensors
- Test this actuator on a volunteer subject to see if it's possible to tell the difference between different settings of vibration intensity
- Find a way to transmit the information from the sensors to the actuators, in a way that allows for a low-signal threshold to be set to zero and a high signal to be set to a maximum value
- Create a simulation for the system

Research hypothesis

Vibration can be used as a means to convey tactile feedback to an amputee through sensors placed in their prosthetic device in an understandable way, making it possible to differentiate different levels of pressure applied.

Methods

Experimental, numerical and statistical methods have been used in completing the tasks and achieving the goal of the thesis.

Scientific novelty and practical value

To date, there is only one prosthetic arm in the market with tactile feedback, and it's only available in the United States. Several laboratories are researching other means of adding tactile feedback to their prosthetic devices, but most of them require undergoing a surgical procedure and an invasive coupling. This project shows the possibility to make tactile feedback in particular and prostheses in general more accessible to a wider population by making a lightweight, small and inexpensive prototype.

1 LITERATURE REVIEW

First, a brief introduction of the anatomy of the arm, hand and skin, as well as the process of amputation will be presented, to set the bases for the feedback problem. Then the history of prostheses and their evolution will lay out the next steps toward better prostheses.

1.1 BIOMECHANICS

1.1.1 ANATOMY OF THE ARM

The arm, not counting the hand, is composed of three bones (the humerus in the upper arm and the radius and ulna in the forearm) and many muscles (see Figure [1](#)).

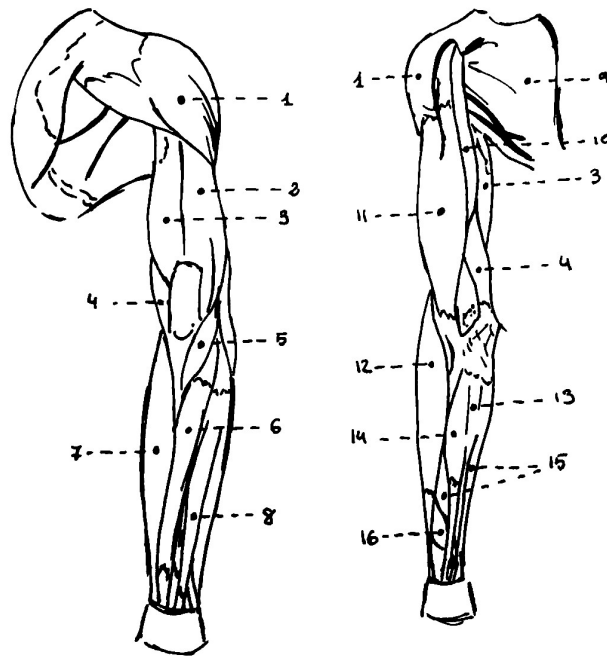


Figure 1: 1- M. Deltoideus. 2- Caput laterale m. tricipitis brachii. 3- Caput longum m. tricipitis brachii. 4- Caput mediale m. tricipitis brachii. 5- M. anconeus. 6- M. extensor carpi ulnaris. 7- M. flexor carpi ulnaris. 8- M. extensor digitorum. 9- M. subscapularis. 10- M. coracobrachialis. 11- M. biceps brachii. 12- M. brachioradialis. 13- M. palmaris longus. 14- M. flexor carpi radialis. 15- M. flexor digitorum superficialis. 16- M. flexor pollicis longus.

To send and receive signals such as temperature, pressure, pain, position or vibration, five main nerves run along the arm (Teach Me Anatomy, 2021):

- Axillary nerve: innervates teres minor and deltoid muscles, connecting the arm to the chest.
- Musculocutaneous nerve: innervates the three muscles of the anterior compartment of the arm: coracobrachialis, biceps brachii and brachialis.
- Median nerve: innervates the posterior compartment muscles of the forearm and the thenar eminence muscles
- Radial nerve: innervates the posterior compartment muscles of the arm and forearm.
- Ulnar nerve: innervates the muscles of the hand, the flexor carpi ulnaris muscle and medial half of flexor digitorum profundus muscle in the forearm.

1.1.2 ANATOMY OF THE HAND

The hand has 26 bones divided into three main sections: the carpus, the metacarpus and the phalanxes (see Figure 2). There are also more than 30 muscles in the hand, that will not be detailed as they don't have much relevance in this topic. The main nerves going to the hand are the median, ulnar and radial nerves, described in the previous section, that branch off into the palm, fingers and back of the hand.

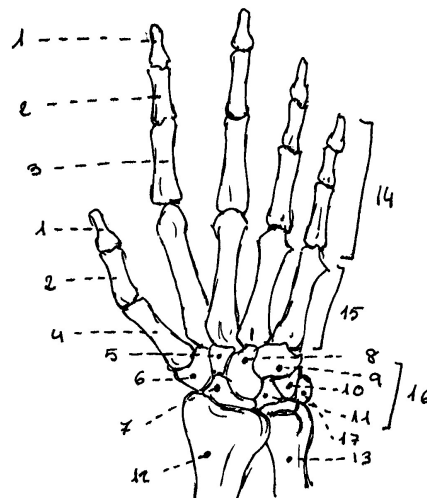


Figure 2: 1- Distal phalanx. 2- Middle phalanx. 3- Proximal phalanx. 4- Metacarpal. 5- Trapezoid. 6- Trapezium. 7- Scaphoid. 8- Capitate. 9- Hamate. 10- Triquetrum. 11- Lunate. 12- Radius. 13- Ulna. 14- Phalanxes. 15- Metacarpus. 16- Carpus. 17- Pisiform.

1.1.3 ANATOMY OF THE SKIN

The skin is the largest organ of the body, and its primary function is to protect it and to serve as a barrier for harmful organisms. It is divided into three main layers (Lopez-Ojeda et al., 2020).

- The epidermis: The outside layer of the skin, that serves as a barrier.
- The dermis: The middle layer of the skin, where the mechanoreceptors and thermoreceptors are.
- The hypodermis: The inside layer of the skin, mostly composed of connective and fatty tissue.

The dermis is the most relevant layer in this essay, as it houses the receptors that will later be used for tactile feedback. These receptors are divided according to function:

- Pacinian corpuscle: These corpuscles are responsible for the sensation of vibration and pressure. They are activated if the change in pressure is sudden, which makes them particularly sensitive to vibrations. The optimal sensitivity of these receptors is 250Hz (Kandel et al., 2000).
- Meissner corpuscle: These receptors respond to low frequency vibrations, between 10 and 50Hz. They adapt quickly to the changes, so they aren't capable of transmitting sustained stimulus (Piccinin et al., 2021).
- Ruffini endings: Allocated in the base of the dermis, these receptors adapt slowly, detecting skin stretch and deformation (Lumen, 2013).
- Merkel receptors: These receptors perceive gentle touch and adapt slowly (Maksimovic et al., 2014).

1.1.4 THE SOMATOSENSORY SYSTEM

The somatosensory system is the part of the nervous system that transmits information about touch, pressure, pain, temperature, position, movement and vibration, which arise from the muscles, joints, skin and fascia (Gleveckas-Martens, 2013).

Through the skin, humans can feel a range of changes in the environment or their bodies, such as the mechanical properties of what they touch (soft, hard, rough...), the shape or the temperature. Some of these properties can also cause the pain receptors to fire, informing the brain of a potentially dangerous contact. All of this awareness is important in daily interactions, as it gives a lot of information about the surroundings in very little time.

The receptors that convey mechanical properties such as vibration, light touch or deformation of the skin have been explained in the previous section. From these receptors, the signals travel to the central nervous system (CNS) and to the primary somatosensory

cortex (PSC) in the brain. The PSC is a region in the postcentral gyrus that processes the somatosensory sensations (see Figure 4a). The signals coming from the whole body are arranged so each part of the body has a proportionate surface of the PSC to process the information that it receives. Some parts of the body have a higher density of receptors than others, and therefore occupy a larger surface than those with a lower density (see Figure 3) (Purves et al., 2008).



Figure 3: 3D figure of the sensory homunculus sculpted by Sharon Price-James. Representation of the human body proportional to the surface occupied in the PSC (Wikipedia, n.d.).

The information about pain is collected by nociceptors. Nociceptors are free nerve endings that fire when a stimuli has caused some kind of damage in the tissue or could potentially do so. The signals from nociceptors travel through the spinal cord to the spinothalamic tract to output on the thalamus, where it's processed (see Figure 4b) (Garland, 2012) .

The information about temperature is collected by warm and cool thermoreceptors. Cool thermoreceptors fire from 34°C to 15°C linearly, and then stay mostly constant even if the temperature drops. Warm thermoreceptors fire from 34°C to 45°C linearly and then keep at the same level. Some of these thermoreceptors also act as nociceptors, and therefore can cause the sensation of pain when touching a very hot or very cold surface (Rogers et al., 2018). These receptors send the signals to the PSC in the same way as the mechanoreceptors.

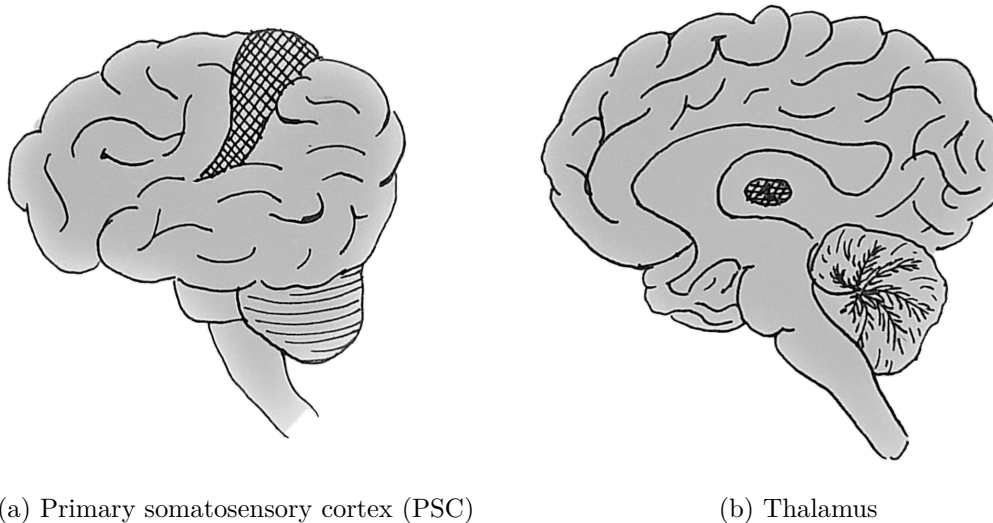


Figure 4: Relevant regions of the brain highlighted with a grid

Neuroplasticity

The concept of neuroplasticity, or the ability of neurons and neural networks in the brain to change and rearrange themselves is an important point to take into account. With the loss of a limb, the brain suddenly has a maladjustment in its structure, and it tries to compensate it by creating new neural pathways and changing others (Rugnetta, n.d.). These changes can be used to teach the brain to read new stimulus as one that it has lost, such as vibration or electrical stimulation as a feeling of touch in a lost limb.

1.2 BASICS OF AMPUTATION

(Maduri & Akhondi, 2020) There are several reasons to perform an upper limb amputation:

- Trauma that cannot be repaired
- Loss of blood supply that cannot be repaired
- Presence of cancerous cells (malignancy)
- Severe contracture
- Congenital deformities
- Infection
- Burns
- Electrical injury
- Frostbite
- Vascular disease

- Complications from diabetes

In some cases, a patient can be born with a shorter or incomplete limb without going through a surgery, but with the same general outcome. However, there might be differences in innervations or skin sensitivity.

An upper limb amputation can happen at different lengths of the arms (see Figure 5), depending on the damage spread. In every case, the goal is to maintain as much of the limb as possible, as it correlates with functionality after the amputation both with a prosthesis and without one.

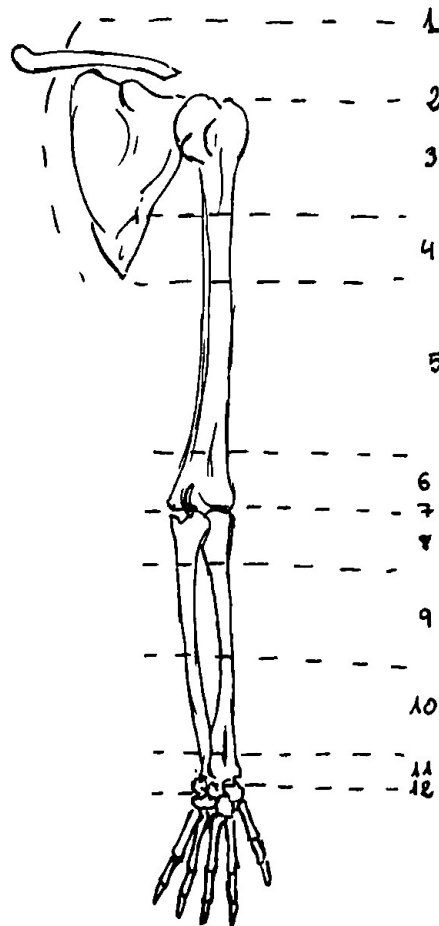


Figure 5: Possible levels of arm amputation. 1- Forequarter amputation (FQ). 2- Shoulder disarticulation (SD). 3- Very short above elbow (AE). 4- Short above elbow (AE). 5- Standard above elbow (AE). 6- Long above elbow (AE). 7- Elbow disarticulation (ED). 8- Very short below elbow (BE). 9- Short below elbow (BE). 10- Long below elbow (BE). 11,12- Wrist disarticulation (WD).

When performing an amputation at any level, the surgeon needs to take into account several things for the best result and recovery, and the possible fitting of a prosthesis. This will make the quality of life of the patient better and allow for more independence and comfort when wearing a prosthesis.

One very important issue is the placement of the scar after the procedure. In an ideal case, the scar would be non-tender, pliable, mobile, and durable, and its placement is not as crucial. However, the scar can sometimes not be ideal, and be hard or prominent. These cases make the placement of scar tissue in the residual limb particularly vital to ease the process of fitting a prosthesis. In addition, the more skin surface available the better, as it decreases pressure while in contact with the prosthesis socket and therefore improves comfort.

To avoid chronic pain, obtaining a well-padded and balanced residual limb is the best course of action. The goal is to keep as much of the functioning muscles as possible to provide strength, circulation, metabolic exchange and proprioception in the limb. The surgeon needs to stabilize the muscles, making sure they are not too tightly fixed, as it would cause severe pain in the patient, or too loosely, as it would not provide the necessary strength and contribute to atrophy of the residual limb.

The treatment of the nerves during the procedure can make a big difference in the final result and the pain suffered by the amputee. The severed nerves can still send electrical signals to the brain, so they must be placed as far as possible from the scar tissue and other contact surfaces, as well as keeping them separated from big blood vessels. Otherwise, the nerve could send signals feeling the vessel's movement and cause a continuous throbbing pain. However, good innervation of the residual limb can help the amputee's functional independence and it can allow the fitting of a prosthesis with tactile feedback, which can help the patient feel the artificial hand as their own.

Blood vessels should be carefully ligated and properly connected to ensure a good irrigation of the residual limb, as a good blood flow in the site can be the difference between a successful recovery or a failed or problematic one. The bone must be treated to make sure that there are no sharp edges that can cause pain later on, and the surgeon must consider the details of the available prostheses for the level of amputation to create a suitable shape for easy fitting. Some pre-operation considerations of possible complications and how to avoid them can also help the patient's recovery (Smith, 2018).

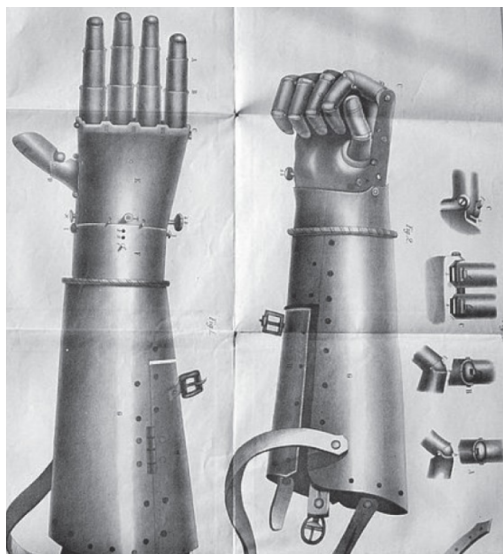
1.3 A BRIEF HISTORY OF ARM PROSTHESES AND THEIR EVOLUTION

Hands are important tools in our daily lives as humans. We use them to communicate with others, as tools, to express ourselves and in general to go about our daily routines

(Leroi-Gourhan, 1996). Because of this, the loss of a hand creates a huge impact in the life of a person, and changes drastically the way of working, communicating with others in society and even self-image. The importance of hands has encouraged a long history of hand prostheses, trying to restore some function or aesthetic to the lost limb for millennia. However, from the engineering point of view, hands are very complicated and delicately tuned machines with a wide range of movements, sensations and uses. This makes the development of useful prostheses a difficult task, and for many centuries, the basic design of prosthetic arms didn't change much.

The first documented hand prosthesis dates back to the Second Punic War (218–201 BCE), and it was an iron hand made for a roman general, that allowed him to raise his shield and therefore go into battle after the amputation (Zuo & Olson, 2014).

The designs for prosthetic hands didn't change much until the middle ages, when the first known prosthesis with some sort of movement is recorded. The owner, Götz von Berlichingen, was a German imperial knight who lost a hand during a siege. His first prosthesis was not much different from the roman one, but the second one had moving parts that allowed him to hold the reins of a horse, a shield or a quill. The knuckles of all the fingers were movable and allowed for a tight grip on the objects (Morton, 2015).



(a) Second prosthetic hand with moving parts



(b) Parts and mechanisms

Figure 6: Götz von Berlichingen's prosthetic hand and its parts (Zuo & Olson, 2014)

The next step on arm prostheses was to make movement powered by other parts of the body of the user. These body-powered prostheses allow the amputee to grab objects and perform simple hand movements without the need of the other hand. The prosthesis is connected to the shoulder, the back or another body part with cables and harnesses, and by moving it a gripping motion is produced. These kinds of prostheses were first developed after WWI, with the need to get injured soldiers back to work, and they allow the users a big level of independence. These prostheses often take the shape of a split hook, and are still widely used nowadays (Zuo & Olson, 2014).

Today, myoelectric prostheses allow the users to control the artificial limb by moving muscles in the residual limb, giving a higher level of independence to the amputees. The electrical signals from the muscles are picked up by sensors and transmitted to a controller in the prosthesis. The speed and force of the movement can be controlled easily. This kind of prosthesis can also be used by people with no arms or damaged nerves or muscles, as any part of the body can be used for controlling the device (Ottobock, 2020).

Hand prostheses have evolved a lot since the first iron hand, gaining new features and allowing for greater independence of the users. However, they are still far from natural hands, lacking range of movement, speed and some vital characteristics such as tactile feedback. To pick up objects, the user needs to rely on visual feedback, which limits the use. The next step in hand prosthetics is to add tactile feedback to the prostheses, getting them even closer to a natural hand and allowing the user to pick things up without the need of visual feedback.

1.4 THE TECHNOLOGY TODAY

There are already some technologies developed that go toward the same goal of providing some sort of tactile sensation in the prosthetic arm. In this section, the types of feedback providers and the prosthetic options available today will be presented, as well as their limitations so far.

Electro-tactile feedback (TENS)

Through light electrical stimulation in the forearm, the sensation of touch can be transmitted in an efficient and adjustable manner. The strength of the electrical stimuli can be adjusted to the user's comfort, avoiding pain and involuntary muscle contractions. This kind of technology has not yet been implemented into a prosthesis, it has only been tested in a lab (Pamungkas & Ward, 2015).

Vibromotors

There are several receptors in the human skin that can transmit information about vibration. This vibration can be associated with a tactile sensation in a specific finger

after some training, where the brain automatically translates the information without the user actively having to think about it (Wijk et al., 2019). This vibration can also improve performance in users with myoelectric prosthesis (Raveh et al., 2018b).

Targeted Sensory Reinnervation

This surgical procedure allows the patient to have a better nervous system around the place of injury, and this can be used to surgically connect these nerves to the prosthesis, achieving a reliable pathway for the signals to go from the prosthesis to the brain. This technology is used in some of the prostheses listed below, but it's an invasive method that requires a specific surgical procedure.

1.4.1 JOHNS HOPKINS APPLIED PHYSICS LABORATORY

One of the most advanced and impressive prostheses developed today is the Modular Prosthetic Limb (MPL) created at Johns Hopkins University laboratory. This arm can perform almost all of the movements a human arm and hand can perform, and has over 100 sensors (see figure 7) (Johns Hopkins Applied Physics Laboratory, 2018).

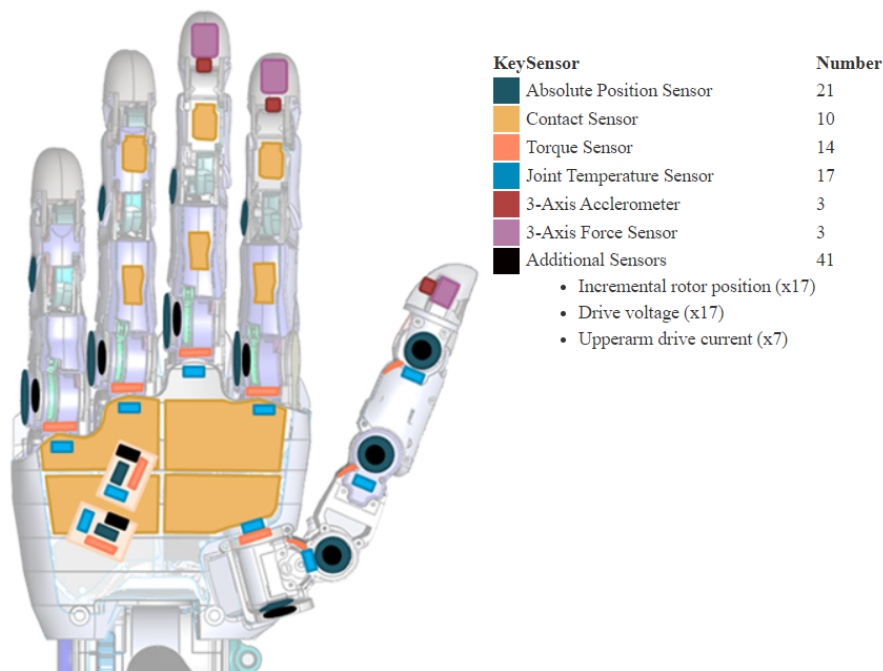


Figure 7: Sensors and sensor placement of MPL (Johns Hopkins Applied Physics Laboratory, 2018)

However, there are only 10 arms like this around the United States, and they are being used for neurorehabilitation research, so they are not available to the general public. In

addition, for this arm to work, the amputee must undergo a specific surgery for targeted muscular re-innervation, which allows the communication between the human brain and the prosthetic limb by positioning the nerves that send touch signals from the fingers in the inside of the residual limb.

1.4.2 THE LUKE ARM

A team in Utah University successfully implemented a sense of touch into their prosthesis (the LUKE arm), letting an amputee perform daily life activities with more confidence and relieve his phantom limb pain (George et al., 2019). The subject was able to pick up an egg without crushing it, by feeling when his prosthesis was touching the surface of the egg. This technology is still being developed, and it also requires an invasive interface so the brain can get the signals the prosthesis is sending. The arm is wired to a computer, so it's still not possible to use it outside the lab, although the team expects to have it separated by this year.

1.4.3 PSYONIC'S ABILITY HAND

The first commercial bionic hand with multi-touch feedback was launched this year by PSYONIC. The Ability Hand is only available in the US, but it offers a non-invasive solution to tactile feedback by using vibration, and it's a lightweight myoelectric controlled arm. The Ability Hand can be fitted to amputees over wrist disarticulation (PSYONIC, 2021).

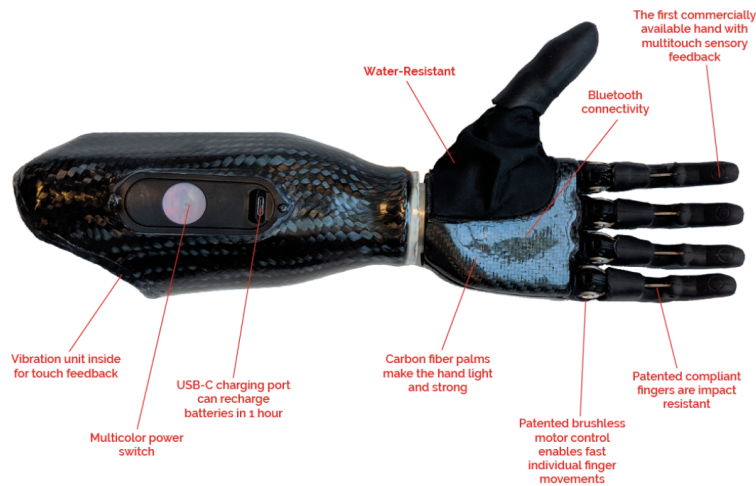


Figure 8: PSYONIC's Ability Hand (PSYONIC, 2021)

1.5 HAPTIC FEEDBACK

Haptic feedback is the technology that allows communication with the user via the sense of touch. This technology is widely used in smartphones and game controllers, which use vibration as a way to convey information to the user. However, there are many uses and different kinds of haptic feedback, from entertainment, to accessibility, to rehabilitation.

Entertainment

The most common and well known use of haptics is in the entertainment industry. The vibrations in phones when a text comes in, or on a game controller when an explosion occurs in the screen. Vibration is usually the choice for these feedbacks, as it is well known, easy to understand and not difficult to implement. Most game controllers have what is known as 'rumble' feedback, where the controller vibrates when a particular thing happens on screen. However, this 'rumble' is not very precise, as it uses spinning motors with a displaced weight. With the launch of the new Play Station 5 (PS5) in 2020, the haptic feedback in the controllers was changed to voice coil motors, that have a larger range of vibrations and are a lot more precise. According to some users, this kind of new feedback made them feel the difference between a character moving through sand or mud and gliding through ice (Jones, 2020).

Accessibility

Haptic technology can also be used to improve accessibility to people with limited vision or hearing. A good example of this is the new technology added in The Aquarium of the Pacific, an aquarium in the United States that has recently added haptic feedback to their new movie theater. They use ultrasound technology to create the illusion of tactile feedback in mid air, associating different sensations to particular moments represented on the screen. This allowed blind and deaf people a more immersive experience (O'Conaill et al., 2020).

Rehabilitation

The field of rehabilitation has been shifting towards 'gamification' in the past years, trying to make rehabilitation less like a chore and more interesting and engaging for the patients. Technologies like Virtual Reality (VR) help people in rehabilitation feel more motivated and overall have a better outcome (Luque-Moreno et al., 2015), and haptic feedback is an important part of it. Some haptic technologies make possible to have telerehabilitation, guiding the patient through the process with tactile cues and providing feedback to let them know if the exercise is being done correctly (Handelzalts et al., 2021).

1.6 THE PROTOTYPE

To date, there aren't many options in the market for arm and hand amputees that include any kind of tactile feedback. Only one prosthesis with this characteristic is on the market, and it's only available on the United States. Many of the prototypes that are being researched need specific characteristics in the amputation or are invasive, making them not suitable for everyone.

The objective of this thesis is to explore the possibility to make a relatively simple and inexpensive setup that could be added to a prosthetic hand and add tactile feedback in a non-invasive way via vibrations in the residual limb. Barometric sensors in the fingertips of the prosthesis would pick up the pressure applied to the fingers and transmit the signal to vibromotors placed in the arm or forearm, which would vibrate in different frequencies according to the amount of pressure received by the sensors. This would allow the user of the arm to distinguish how much pressure they are applying with the prosthesis, and control the force accordingly.

To reach this goal, first the elements are tested individually, seeing if they can work under the conditions needed. The sensors are tested by picking up objects with different weights that could be part of daily life activities. The motors are tested by attaching them to a subject's arm and setting it to different intensities, making sure the subject is capable of distinguishing all of the settings consistently. Then, all the elements are put together in a simulation to prove that the system can work as intended, and finally an experiment is done to discern if the subject is able to associate vibration and pressure exerted.

This model of prosthetic, inexpensive, light and non-invasive will be available to a wider population. The tactile feedback can greatly improve the performance of daily life activities and potentially alleviate phantom limb pain, in the cases when it is present. This tactile feedback will also provide accessibility to people with other disabilities, such as blindness, allowing them to feel around them with the prosthetic device.

2 METHODOLOGY

Presented in this section are the procedures followed to reach the objectives and prove the hypothesis, the experiments and simulations as well as an overview of the whole process followed during the research of this thesis (see Figure 9).

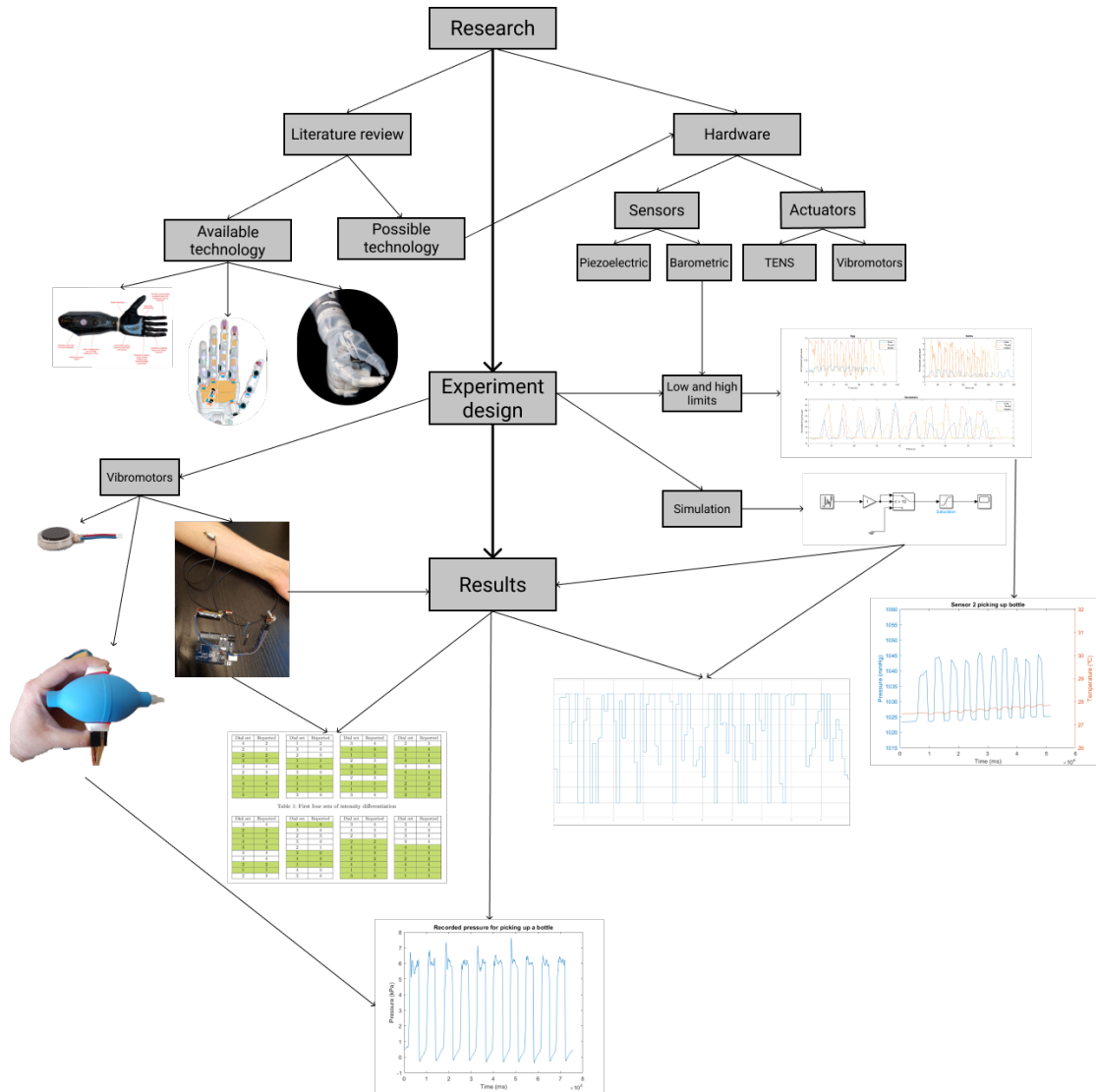


Figure 9: Schematics of the thesis research

2.1 GENERAL PROCEDURE

In order to train the prosthetic user to associate gripping force modulation with vibration-based feedback expressed through different vibration levels and patterns it is essential to estimate what force is required to pick and hold everyday objects, starting from lighter (for example, egg) and ending with heavier (laptop or skillet). Weight values of selected items are provided in Table 1. In this case the weights have been divided into three sections: Under 100g, between 100g and 1000g and above 1000g. These levels, however, can be changed at any point depending on the subject's specific needs and routine. To see the relationship between the weights and the pressure, several objects with different weights were lifted with the sensors by applying the force horizontally (see Figure 10), and a linear regression was fitted, with a $r^2 = 0.9608$.

Object example	Approximate weight	Vibration setting
Egg	50g	1
Set of keys	80g	1
Medium apple	150g	2
Coffee mug, empty	300g	2
Dinner plate	400g	2
Coffee mug, full	500g	2
Tablet	900g	2
Hardcover textbook	1200g	3
Pack of flour	2000g	3
Laptop	2300g	3
Iron skillet	3500g	3

Table 1: Everyday object examples and their average weight

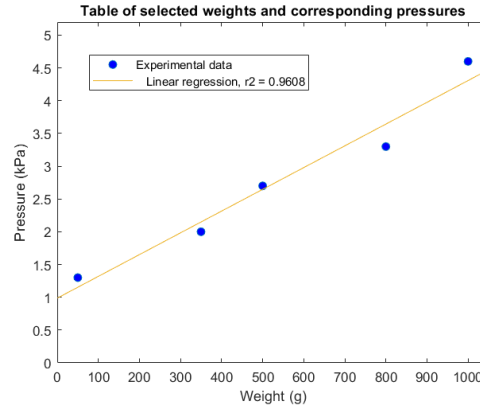


Figure 10: Average weights vs. pressure and fitting

These divisions will serve to set the motor limits to change vibration settings. The vibration intensity is set through the Arduino software, where it can take any values between 0 and 255. The values between 0 and 80 are not intense enough to be felt, so the

actual range of vibration goes from 80 to 255. The first setting alternates between 0 and 100 units (see Figure 11a), the second setting alternates between 100 and 200 units (see Figure 11b) and the third setting has a continuous signal of 200 units (see Figure 11c).

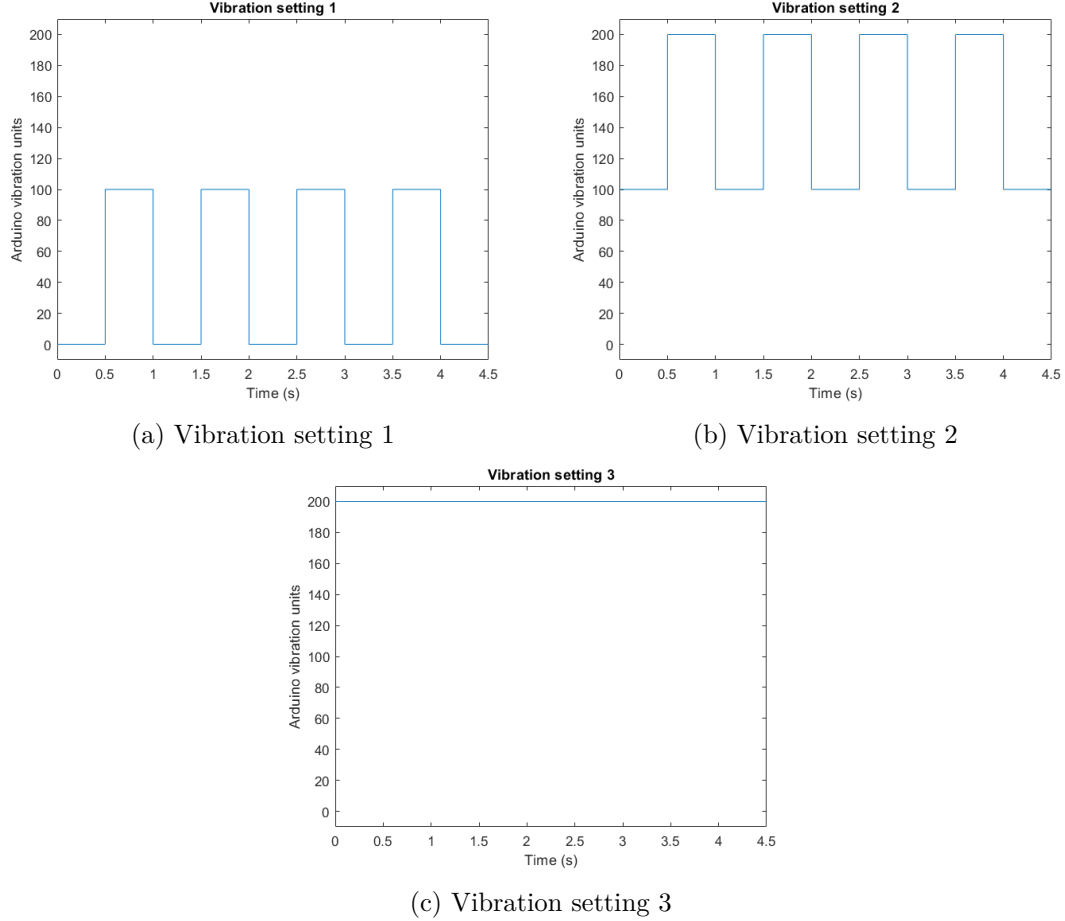


Figure 11: Vibration settings

The first weight division was selected to cover the lightweight objects and keeping the range rather small to avoid crushing or squeezing them. Additionally, anything under 40g would not activate the motors. The second division is larger, including medium-weight objects that need a slightly stronger grip to be picked up. The last division is for heavy objects and it's the largest, with objects that need a larger amount of pressure in the grip to be picked up or moved. These levels can be changed to accommodate the user and their specific needs, and more vibration settings could be added if needed. The experiments were selected to cover both extremes of the range, very light things, represented with an egg, and heavy things, represented with the full glass bottle.

The experiments presented on this project are pointed towards a one case study, seeking to get a proof of concept and not to make a statistical analysis of the population.

2.2 SENSORS

The sensors used throughout the whole project are barometric sensors, although two different kinds have been used. SPI barometric sensors with hard silicone and GY-63 barometric sensors with a softer silicone and a plastic case on the bottom side.

2.2.1 SPI BAROMETRIC SENSORS

The first signal input was captured by miniature SPI barometric sensors. These sensors are factory calibrated to pick up a range of absolute pressures from 375mmHg to 863mmHg, with an accuracy of 1mmHg. The sensors are encased in a silicone cover that helps redistribute the pressure applied and can also be easily shaped into a fingertip-like sensor (see Figure 12). This shape is not only an aesthetic decision, as it can be easily inserted into the prototype, but it also clarifies the signal input and it simulates the gripping action better than a flat sensor.

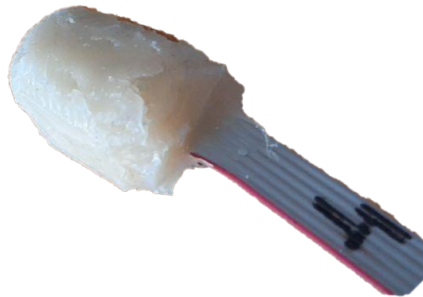


Figure 12: One of the barometric sensors used

To gather data the sensors were connected to an Arduino UNO board which displayed two pressure values per second. This information can then be input in MATLAB to be analyzed and plotted. To minimize the signal noise (see Figure 13) the median filter `medfilt1` of a 7th order was applied to all the data sets.

To get comparable results with the different sensors the process of calibration is particularly important. For this each sensor was placed on a flat surface for 30 seconds and then pressed down with a weight of 1046g for another 30 seconds. The results show a

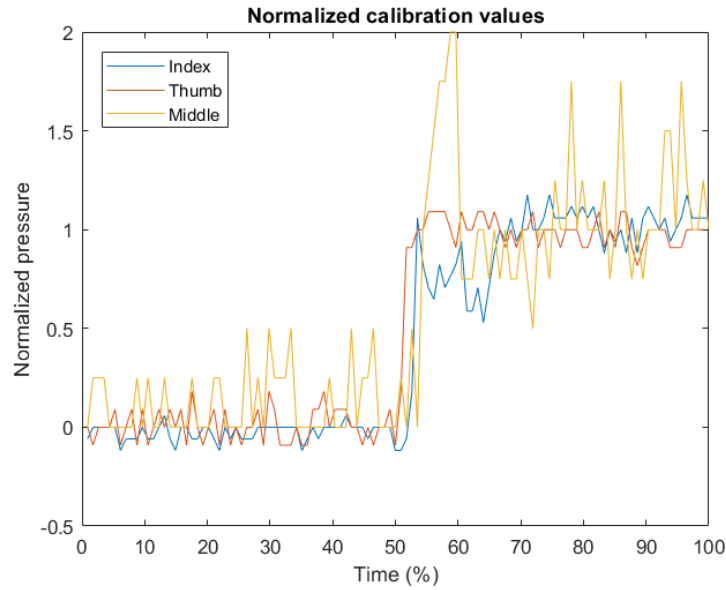


Figure 13: Values of calibration before filtering the signal

variance of 1mmHg for all the sensors even during rest, but also present a clear peak after applying the weight. However, the sensor assigned to the ring finger stayed at a constant value during the whole calibration process, showing that there is a problem with the sensor which was then left out of the prototype. The main fingers used for any daily life activity are the thumb, the index and the middle finger, and the focus will be on them. The results of these calibrations were normalized to allow the comparison between them, getting the final result as shown in Figure 14.

To test the range of the sensors several three actions were performed 10 times each, using the hand with the sensors attached to the fingertips and recording the data from one sensor at a time, repeating the process for each sensor connected. In every set all sensors were attached to the hand, even if not connected to the computer, to avoid changes in the way the actions were performed. For a minimum value, the action selected was picking up an egg. For a maximum value, picking up a glass bottle full of water. For a middle value a handshake, an activity that involves the whole hand but it's different from picking up an object.

2.2.2 GY-63 BAROMETRIC SENSORS

The sensors used for the final experiment are GY-63 barometric sensors that can measure pressure and temperature. Barometric sensors are very sensitive to temperature changes, changing the reading of pressure even if there is none being applied. By gathering temperature as well as pressure data, the readings are more reliable and the

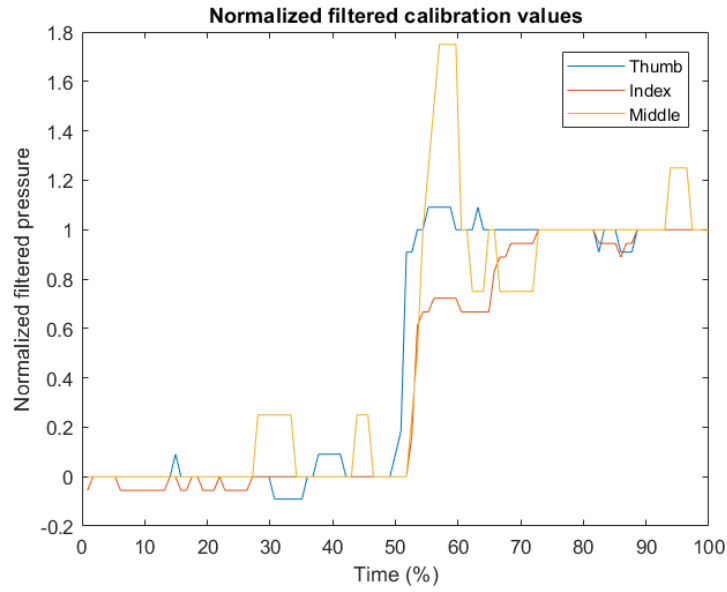


Figure 14: Normalized values of calibration of the three working sensors

offset can be corrected. The sensors are connected to an Arduino UNO board to collect the data. The shape of this sensors, however, is different to the previous set. The new sensors have a flat surface, and the silicone used has a better grip than the one used in the previous set (see Figure [15](#)).



Figure 15: GY-63 barometric sensor

As these sensors have a very noticeable reaction to temperature it's important to

let them warm up before starting each experiment (see Figure 16). The current going through the sensor generates heat, and it's better to wait for the sensor to reach a constant temperature before starting each experiment. After the sensors are warmed up they are attached to the fingertips and used to pick up the objects while recording the data.

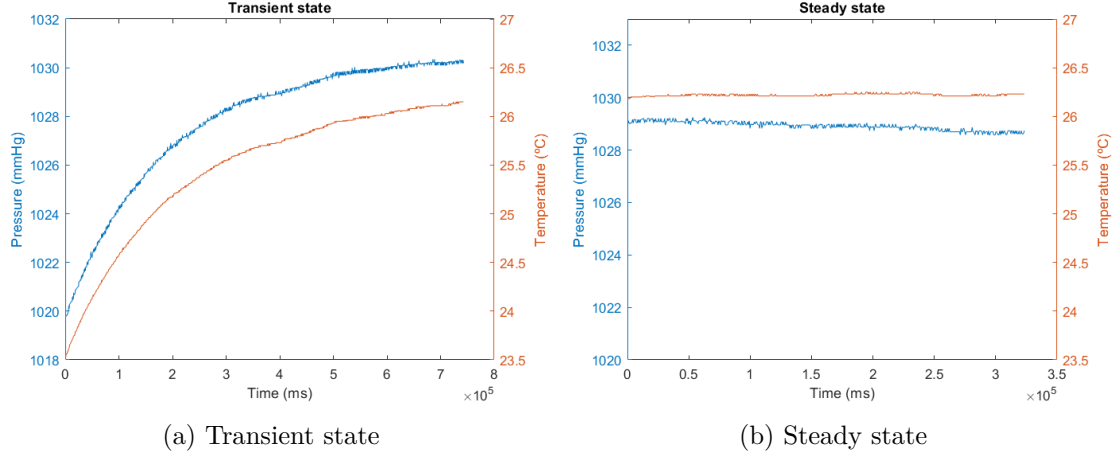


Figure 16: Evolution of the sensor signal with temperature while at rest

2.3 VIBROMOTORS

For the actuators the option chosen were vibromotors, to get different vibration intensities and patterns related to the pressure received by the sensors. The original idea was to use coin vibromotors, as they are small and flat and easy to fit anywhere in a prosthetic device. The first vibromotors used were not strong enough for the user to feel the vibration even in the highest setting, so some experiments were performed with DC motors with a displaced weight. Lastly, more powerful coin vibromotors with enough intensity could be used.

2.3.1 INTENSITY DIFFERENTIATION EXPERIMENT

One volunteer was recruited in the study to estimate the ability of the user to differentiate intensities of vibration with a continuous pattern. The vibromotor used here was 3V DC vibromotor with a displaced weight, 19x10x8mm in size. The vibromotor, connected to a power source and an Arduino board (see Figure 17) was attached to the skin in the subject's arm (see Figure 18). Firstly, the subject was asked to indicate when the feeling of vibration started while progressively turning up the frequency. Once the lower limit was set, the whole range of the potentiometer was divided into 4 equal

sections. The sections were named from 1 to 4, and the subject went through three runs of each section to get familiarized with the difference between them. Then, he was blindfolded and wore noise canceling earphones to avoid sound or sight bias. He was then asked to report the number corresponding to the vibration, going through four sets of ten numbers that were randomly generated. Between numbers the motor was turned off completely and then back again to the corresponding number, to mimic the action of grasping an object from an open hand position. This process was performed on two consecutive days, 24h apart. The subject was informed of his results after each set of 10 numbers.

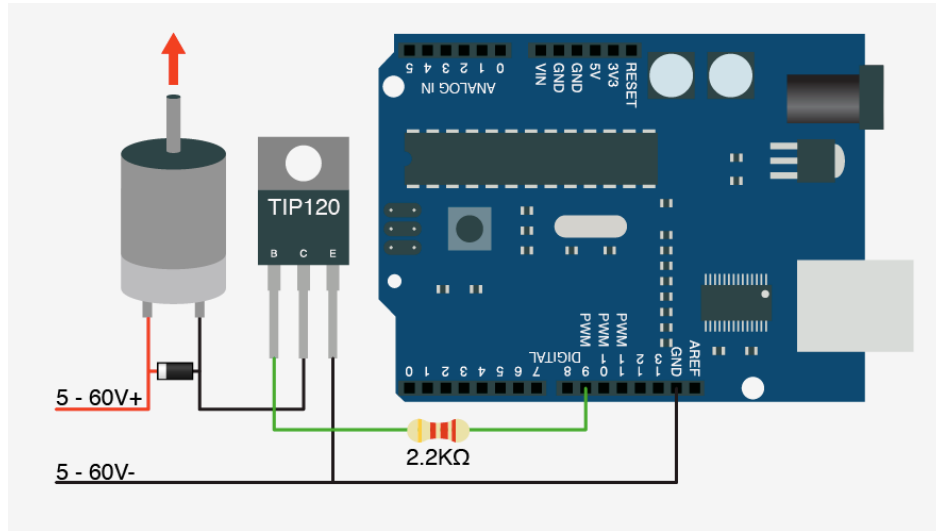


Figure 17: Schematics of the Arduino UNO connections to test the vibromotors

2.3.2 THE PROSTHESIS

The prosthesis for this project is a basic prosthetic hand controlled by servomotors. It's not designed to be worn, but for the purpose of the experiments it doesn't need to be. The hand is controlled through a glove that has springs on each finger (see Figure 19). Each spring has an infrared source in one side and a light sensor on the other side. This changes the amount of light that reaches the sensor when the fingers are bent inside the glove, and these changes move the servomotors, allowing the control of the hand remotely. However, controlling the hand is difficult and requires some training, as there is some lag between the movement of the glove and the movement of the prosthesis, and a small bending of the fingers can become a big rotation of the servomotors, which amplifies every movement.

The initial idea for the experiment was to use this hand to pick up the objects and

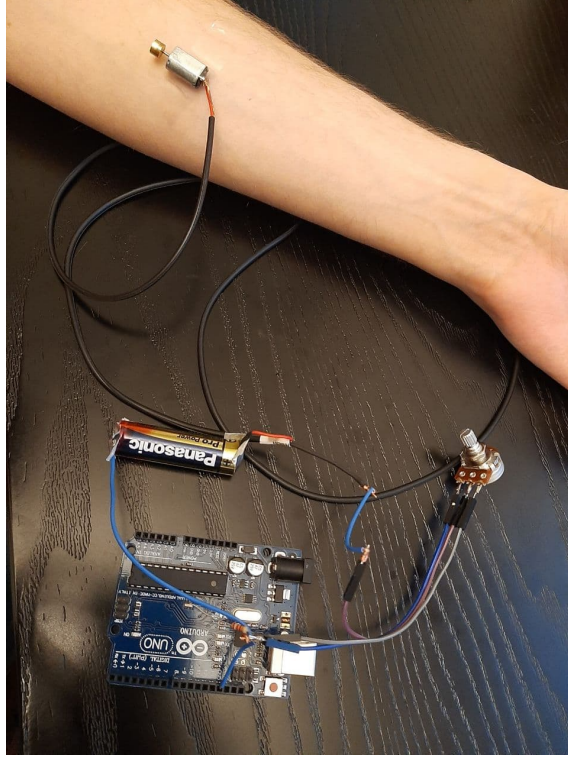


Figure 18: Experimental setup to test the vibromotor

prove that the sensors were working as intended. However, the servomotors in the prosthesis are not strong enough to activate the sensors, even when the subject is completely closing the hand.

2.3.3 THE DYNAMOMETER EXPERIMENT

As the prosthetic hand was not fit for use in the final experiment as originally intended, the experiment's design changed to accommodate the circumstances. The new experiment was performed with a handheld dynamometer. The experiment was divided in two main parts: in the first one, the calculation of the expected result; in the second one, the experimental outcome.

For the first part, the values expected were calculated based on the limits set for the sensors previously and the offset, getting a final value of 1.3kPa for picking up an egg and 4.5kPa for the bottle. The dynamometer itself had an offset of +0.4kPa that was added to get the final expected values of 1.7kPa and 4.9kPa respectively.

For the expected results, the values were recorded by pressing the dynamometer while

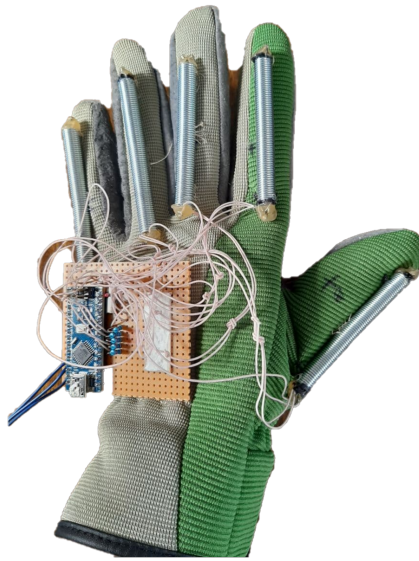


Figure 19: Glove to control the prosthetic hand

looking at the screen and trying to reach the intended value as precisely as possible. The pressure was kept for three seconds and then three seconds of rest between peaks. For the recorded results, the subject held the dynamometer with the sensors in the fingertips, pressing the sensors against the device (see Figure 20). The vibromotors connected to the sensors were pressed against the forearm in opposite places. Then, without looking at the screen and guided only by the vibration of the motors, the subject had to replicate the expected results by pressing the dynamometer until the vibromotors were activated, stopping for three seconds and letting go for another three seconds.

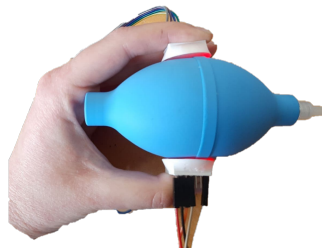


Figure 20: Dynamometer held with barometric sensors

The same procedure was followed for the limit set by the bottle, with one difference. In the case of the bottle the sensors were not activated even when a higher force was applied to the dynamometer. This is caused by the mechanical properties of the device, which is deformable and too soft for that pressure to be registered by the sensors. This

issue was fixed by adding a hard flat surface between the dynamometer and the sensors.

2.4 SIMULINK SIMULATION

For the sake of completion, a simulation was designed in SimuLink to mimic what the circuit would look like when using electronic components instead of Arduino UNO boards (see Figure 21).

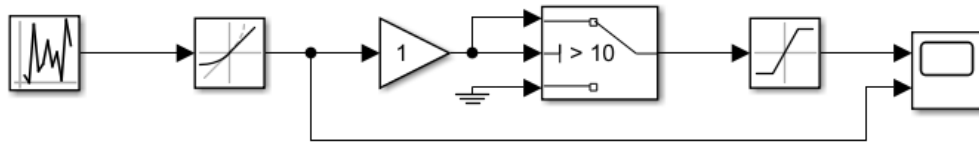


Figure 21: SimuLink simulation of the prototype

The sensor input was simulated with a uniform random number generator, in a similar way as it was previously done for the vibromotor experiment. The values ranged from 0 to 100 (see Figure 21), mimicking what could be a normal use of the prosthesis, going from grabbing light things to heavier things, from an open hand (0) to the maximum grip possible (100), and all the possible combinations, like softening a grip that's too strong or tightening the hand to avoid slipping. The input signal is then passed through a rate limiter to smooth it, avoiding instant peaks or drops in pressure.

The signal is then processed with a low pass filter under 70 units, to represent the maximum value perceived by the sensors. In an actual circuit, this filter can be made with a resistor and a capacitor, which are very small elements and therefore will not add significant weight or occupy a lot of space. For the signals under 10, a switch was added. This switch will send the signal to 0 if the input is below 10, and pass the input if it is above it. This can also be set using a transistor, which is also a very small element. Finally the motor, which will turn at different speeds according to the input voltage received.

Each of the sensors in the fingers would have a similar circuit from sensor to motor. These circuits could be individually adjusted to the user's preference for a more comfortable and personalized experience, as the sensibility in different parts of the arm might be different, or the user might find particularly important to have a higher or lower sensibility in a specific finger.

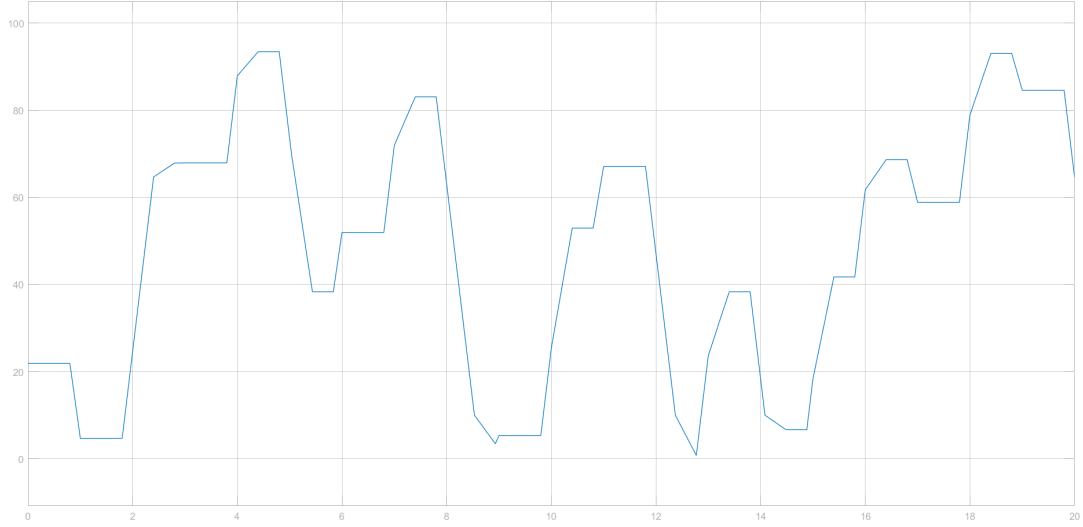


Figure 22: Input signal

3 RESULTS

3.1 SPI BAROMETRIC SENSORS

With the first set of sensors only one could send signals to the computer at a time, so the results for each sensor in the experiments can't really be compared (See Figure 23). The peaks in pressure don't line up, as the timing differed in each run of the experiment. In addition, the pressure applied can be different each time the action is performed, so the results are not really comparable.

Although these results are not good for the final product, we can still extract some information that might prove useful. When picking up an egg, a very delicate task, the pressure each time the action was done is quite constant in every finger. This object was selected for the lower range of the weights in Table 1. This can be very helpful to set up the lower limit of the actuators in the final prototype without the danger of making it too high or it being too inconsistent. A lower limit that's too low can cause discomfort by sending signals continuously in unnecessary situations, such as having the hand inside a pocket or wearing a protective glove or cover. If the lower limit is too high, the user might, for example, break the egg while trying to pick it up, which can cause problems in the prosthesis' hardware.

In the second experiment, the action required to pick up a glass bottle full of water, weighing about 1kg to cover the upper limit of the whole range set in Table 1. Due to the geometry of the bottle and the sensors, the bottle sometimes slipped or was harder to pick up, so the difference between repetitions is more significant. However, the upper

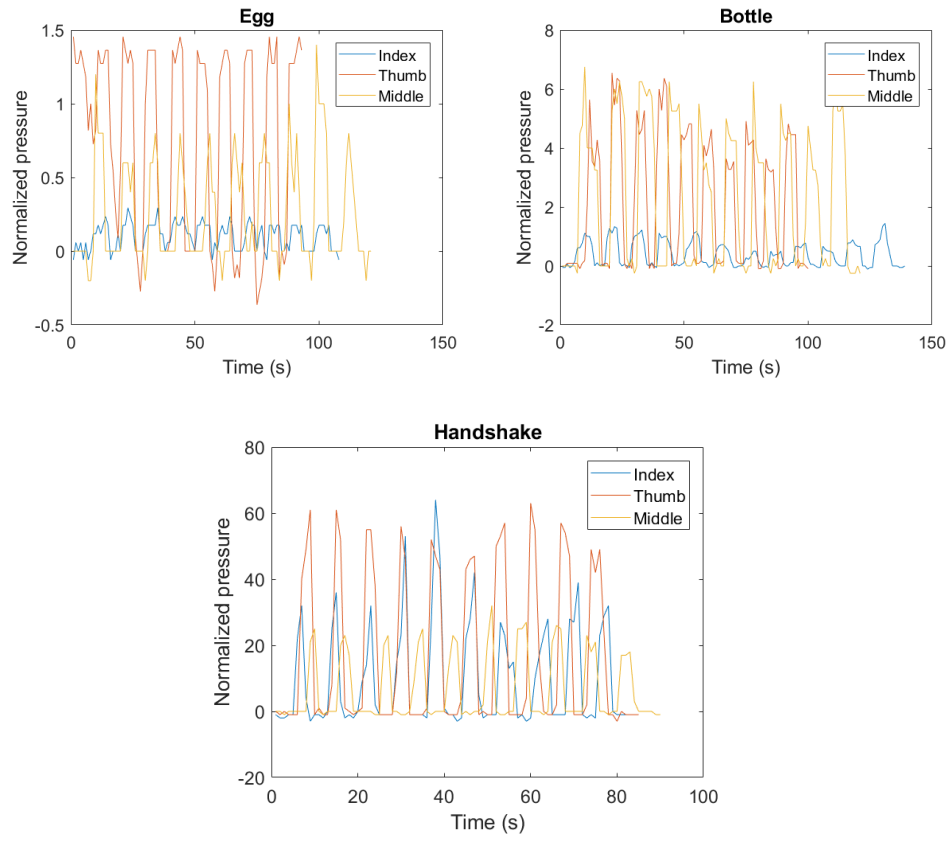


Figure 23: Raw results for SPI sensors

limit for the actuators is not as crucial as the lower limit, as it doesn't risk breaking things that could do damage to the prosthesis, such as an egg or fruit.

3.2 GY-63 BAROMETRIC SENSORS

The values for the second set of sensors were clearer and were taking in account the temperature changes (see Figure 24). These measurements were taken to prove the viability of the sensors and to get the pressure limits to later divide the intensity of the vibromotor into appropriate sections.

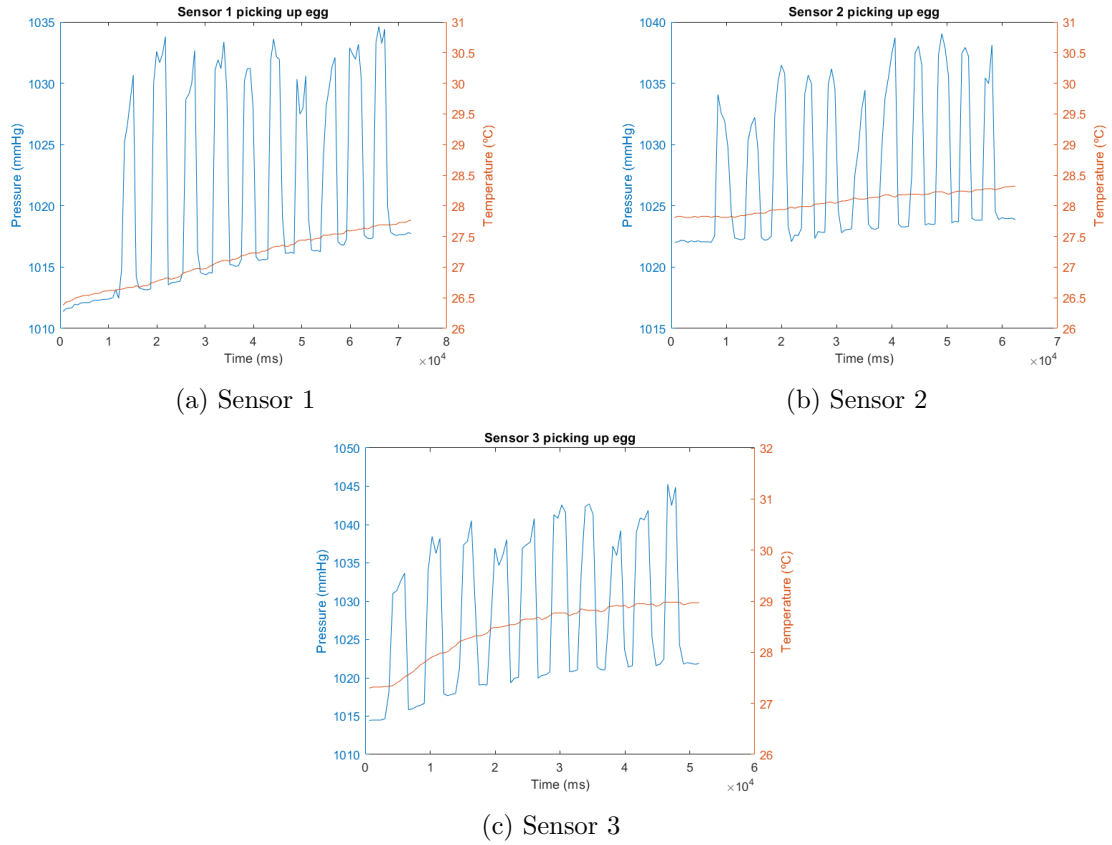


Figure 24: Pressure and temperature measurements of the three sensors for the lower limit, $n=10$

Due to differences in the silicone and the geometry of each sensor, there is a difference in the absolute values and therefore the limits must be set individually. For the first sensor, the lower limit was set at 1025 mmHg, for the second and third it was set at 1030 mmHg.

The second limit was set by picking up the bottle. The same experiment as with the egg was done, picking up the bottle ten times with each sensor. With this data (see Figure 25), the second stage of vibration was set. In this case, at 1040 mmHg for all three sensors.

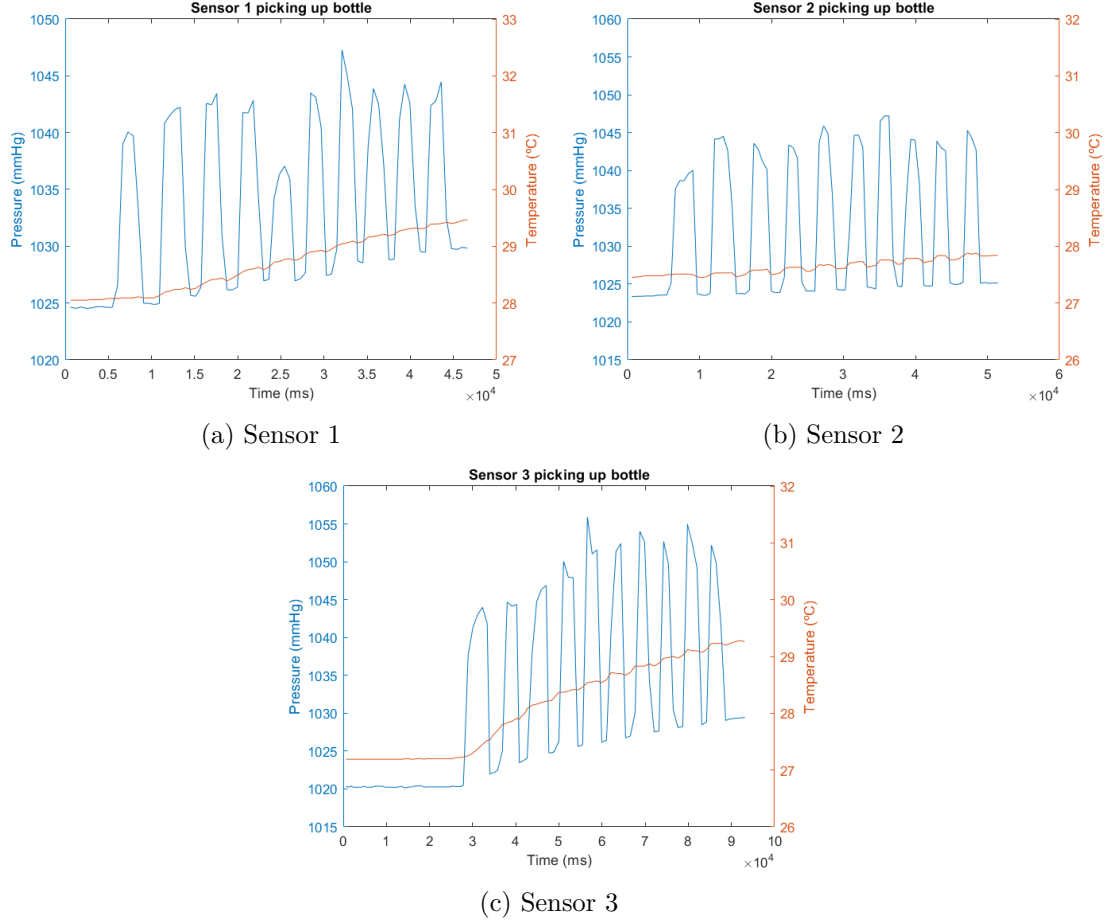


Figure 25: Pressure and temperature measurements of the three sensors for the upper limit, $n=10$

3.3 VIBROMOTORS

In the intensity differentiation experiment, the answers given by the subject are presented in tables 2 and 3.

Dial set	Reported	Dial set	Reported	Dial set	Reported	Dial set	Reported
4	2	1	2	3	4	2	3
2	1	3	4	4	4	4	4
2	2	2	3	1	1	1	1
3	3	1	1	2	3	4	4
3	4	4	4	3	3	3	4
2	3	3	4	2	2	4	4
1	1	1	1	2	3	1	1
4	4	1	1	1	1	2	2
1	1	4	4	1	1	3	3
4	4	3	4	3	4	3	3

Table 2: First four sets of intensity differentiation

On the first set, the subject reported being confused by the lack of intensity of the motor at first, therefore misinterpreting the value he was feeling, which explains the significant difference on the first value of the set, off by two numbers instead of the usual error of one number. However, he felt after a few tries he was getting better at discerning the differences between the numbers. He also reported that the difference between 3 and 4 was the hardest to discern.

The first and third set of the first day (see Table 2) have six right guesses and four mistakes. The second set has five right guesses and five mistakes, and the last set has eight right guesses and only two mistakes. Overall, the most common mistake was reporting a 3 as a 4, done 7 times, followed by reporting a 2 as a 3, done five times. 1 and 4 were misreported only once each.

Dial set	Reported	Dial set	Reported	Dial set	Reported	Dial set	Reported
3	4	4	4	3	4	3	4
2	2	3	4	4	3	2	3
1	1	2	3	2	3	3	4
4	4	3	4	2	2	3	4
3	3	2	1	4	4	4	4
3	4	2	2	4	4	1	1
3	4	4	4	2	2	2	2
2	2	1	1	4	4	4	4
1	1	4	3	1	1	1	1
2	3	3	4	3	3	1	1

Table 3: Second four sets of intensity differentiation

In the second day (see Table 3), the first and last sets have 6 right guesses and 4 mistakes, the second one has 4 right guesses and 6 mistakes, being the worst result of all and the third set has 7 guesses and 3 mistakes. It's interesting to note that in the last two sets of the second day the mistakes are only in the beginning, then having all the right guesses in a row. Overall, the first number was only correctly identified once.

To identify the number of right guesses and the variance of each error the results have been written in the form of a confusion matrix. In the diagonal the amount of correct guesses. In the rest of the positions, the number of times each setting was mistaken for another one. If a 2 was mistaken for a 3, it would add a count one position to the right of the diagonal. If it was mistaken for a 1, it would add a count one position to the left. The ideal result would be having a diagonal matrix, where all of the guesses are correct guesses. The closest the highest values are to the diagonal, the better, meaning the error when making a mistake is smaller.

For the first set of day 1:

$$\begin{pmatrix} 2 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 2 \end{pmatrix}$$

For the second set of day 1:

$$\begin{pmatrix} 3 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 3 \\ 0 & 0 & 0 & 2 \end{pmatrix}$$

For the third set of day 1:

$$\begin{pmatrix} 3 & 0 & 0 & 0 \\ 0 & 1 & 2 & 0 \\ 0 & 0 & 1 & 2 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

For the fourth set of day 1:

$$\begin{pmatrix} 2 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 2 & 1 \\ 0 & 0 & 0 & 3 \end{pmatrix}$$

For the first set of day 2:

$$\begin{pmatrix} 2 & 0 & 0 & 0 \\ 0 & 2 & 1 & 0 \\ 0 & 0 & 1 & 3 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

For the second set of day 2:

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 3 \\ 0 & 0 & 1 & 2 \end{pmatrix}$$

For the third set of day 2:

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 2 & 1 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 3 \end{pmatrix}$$

For the fourth set of day 2:

$$\begin{pmatrix} 3 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 3 \\ 0 & 0 & 0 & 2 \end{pmatrix}$$

To get more reliable results from the experiment in section 2.3.1, the sum of the ma-

trices gives an overview of all the right guesses and the mistakes. It is important to note that on the first set, the subject reported being confused by the lack of intensity of the motor at first, therefore misinterpreting the value he was feeling, which explains the significant difference on the first value of the set, off by two numbers instead of the usual error of one number. However, he felt after a few tries he was getting better at discerning the differences between the numbers. He also reported that the difference between 3 and 4 was the hardest to discern.

The matrix of day 1:

$$\begin{pmatrix} 10 & 1 & 0 & 0 \\ 1 & 3 & 5 & 0 \\ 0 & 0 & 4 & 7 \\ 0 & 1 & 0 & 8 \end{pmatrix}$$

The matrix of day 2:

$$\begin{pmatrix} 7 & 0 & 0 & 0 \\ 1 & 6 & 4 & 0 \\ 0 & 0 & 2 & 10 \\ 0 & 0 & 2 & 8 \end{pmatrix}$$

The overall result of the experiment:

$$\begin{pmatrix} 17 & 1 & 0 & 0 \\ 2 & 9 & 9 & 0 \\ 0 & 0 & 6 & 17 \\ 0 & 1 & 2 & 16 \end{pmatrix}$$

The accuracy of the confusion matrices is given by:

$$Accuracy = \frac{\sum_{i=1}^4 \frac{tp_i}{tp_i + fp_i}}{4} \quad (1)$$

where tp is the number of true positives and fp is the number of false positives.

$$Accuracy_{day1} = 0.227 + 0.083 + 0.091 + 0.222 = 0.623 \quad (2)$$

$$Accuracy_{day2} = 0.250 + 0.130 + 0.042 + 0.200 = 0.622 \quad (3)$$

$$Accuracy_{total} = 0.236 + 0.113 + 0.065 + 0.210 = 0.624 \quad (4)$$

The closest the result is to 1, the better the result. In this case, the results from each day are consistently over 0.5, which suggests that the results are not pure chance, but it's still far from a good result. This pointed into the direction of making the vibration settings not continuous, as explained in the methodology section, and instead use different vibration patterns.

Looking at the individual matrices, there's a clear problem with settings 2 and 3, which more often than not get mistaken for a higher setting, particularly 3 to 4. This suggests that either the settings were not sufficiently different or that the subject still needs to train with the hardware to be able to more reliably tell the difference. However, settings 1 and 4 were rarely mistaken, 1 being the more consistently guessed properly, only being mistaken once. This is the most crucial setting, as it is the one used to pick up fragile objects and it could potentially prevent the prosthesis from squeezing or breaking them, causing damage to the hardware.

3.4 DYNAMOMETER EXPERIMENT

The raw results from the final experiment (see Figures 26 and 27) give a general idea of the success of the experiment, but a better analysis can be done.

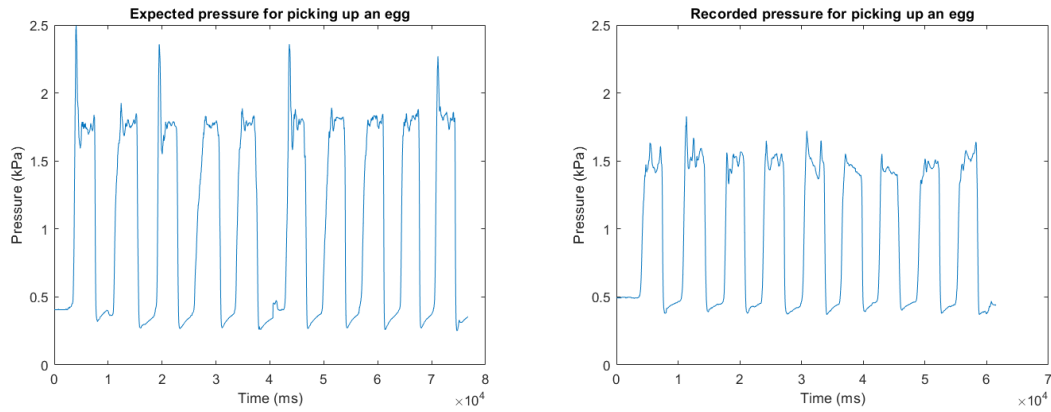


Figure 26: Expected and recorded pressure for the lower limit

For the statistical analysis of each run, all the peaks were aligned to be able to easily compare them (see Figure 28). Then the mean and standard deviation of each run was plotted, and the average and noise of each plateau was numerically calculated.

Results for the expected pressure for the egg in kPa:

Average of each plateau:

$$1.779 \pm 0.023$$

Average of all plateaus:

$$1.779 \pm 0.040$$

Noise of each plateau:

$$0.031$$

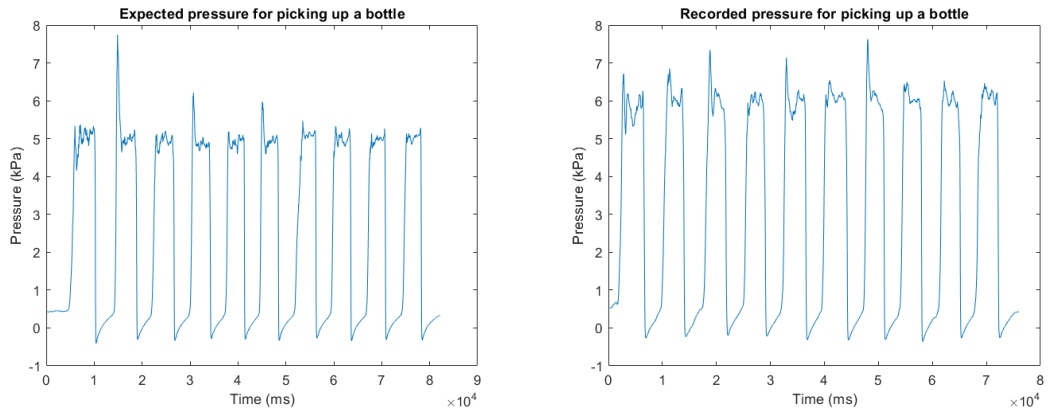
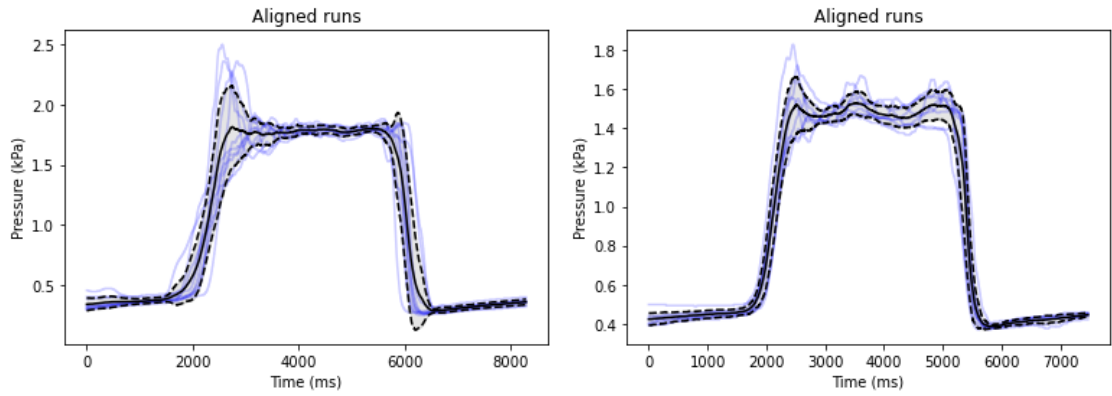


Figure 27: Expected and recorded pressure for the upper limit



(a) Aligned peaks of the expected pressure for the lower limit, mean and standard deviation (b) Aligned peaks of the recorded pressure for the lower limit, mean and standard deviation

Figure 28: Aligned peaks for the lower limit, mean and standard deviation

The results show a very consistent run, where the standard deviation is very small for each plateau and for the overall set. In the individual plateaus the standard deviation is smaller than the noise, and only slightly bigger in the total average. These results are what would be expected of a control run, and need to be compared with the recorded results (see Figure 28b).

Results for the recorded pressure for the egg in kPa:

Average of each plateau:

$$1.489 \pm 0.036$$

Average of all plateaus:

$$1.489 \pm 0.054$$

Noise of each plateau:

$$0.035$$

The most notable difference here is the average, 0.29kPa lower than the expected run (see Figure 29). This can be controlled in the motor settings by changing the threshold. The standard deviation is more consistent that in the control run, but also larger in each peak and in average, while the noise level stays the same.

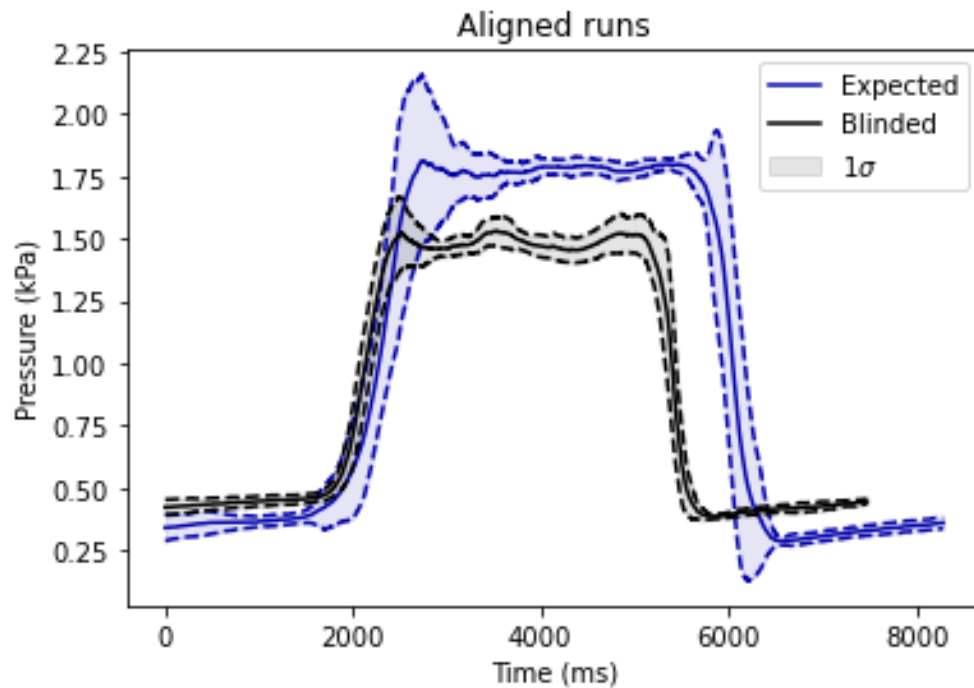
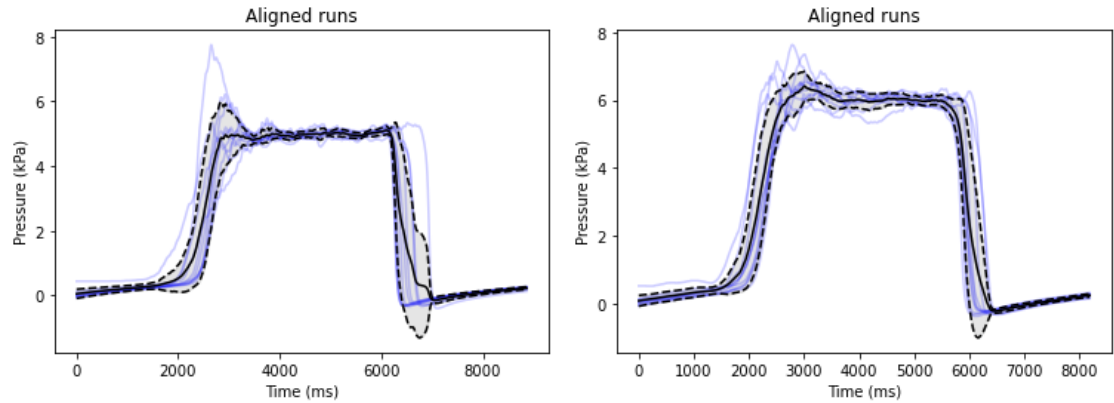


Figure 29: Average expected and recorded aligned runs for the lower limit

The data for picking up the bottle (see Figure 30) show similar results.



- (a) Aligned peaks of the recorded pressure for the upper limit, mean and standard deviation
 (b) Aligned peaks of the recorded pressure for the upper limit, mean and standard deviation

Figure 30: Aligned peaks for the upper limit, mean and standard deviation

Results for the expected pressure for the bottle in kPa:

Average of each plateau:

$$4.971 \pm 0.089$$

Average of all plateaus:

$$4.976 \pm 0.129$$

Noise of each plateau:

$$0.088$$

Again, all the runs are very consistent, with the average of the plateaus being inside the standard deviation limits, which is the expected result of a control run. There is a bigger deviation at the beginning of the plateaus caused by compensation when trying to reach the pressure level, but it's fixed very fast and the noise in the rest of the plateau is very small.

Results for the recorded pressure for the bottle in kPa:

Average of each plateau:

$$6.004 \pm 0.165$$

Average of all plateaus:

$$5.996 \pm 0.227$$

Noise of each plateau:

0.136

In this case the difference between the averages is 1.02kPa, but the recorded pressure is larger than the expected one (see Figure 31). This can also be corrected in the Arduino code, and in this case might be caused by having to add a flat hard surface between the sensors and the dynamometer. Although the standard deviation is larger than in the expected measurements, the average is still within limits.

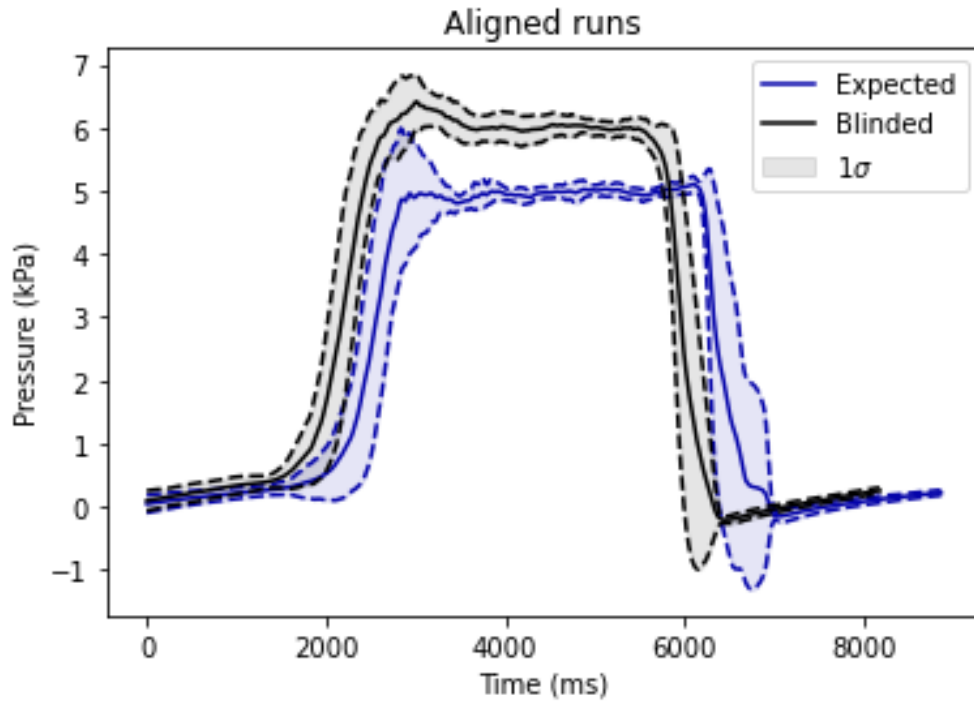


Figure 31: Average expected and recorded aligned runs for the upper limit

The difference between the expected and recorded pressure is 16.3% in the case of the egg and 20.5% in the case of the bottle.

3.5 SIMULINK SIMULATION

In the output signal of the simulation (see Figure 32) the result of the processing is shown in red along with the input signal, in blue.

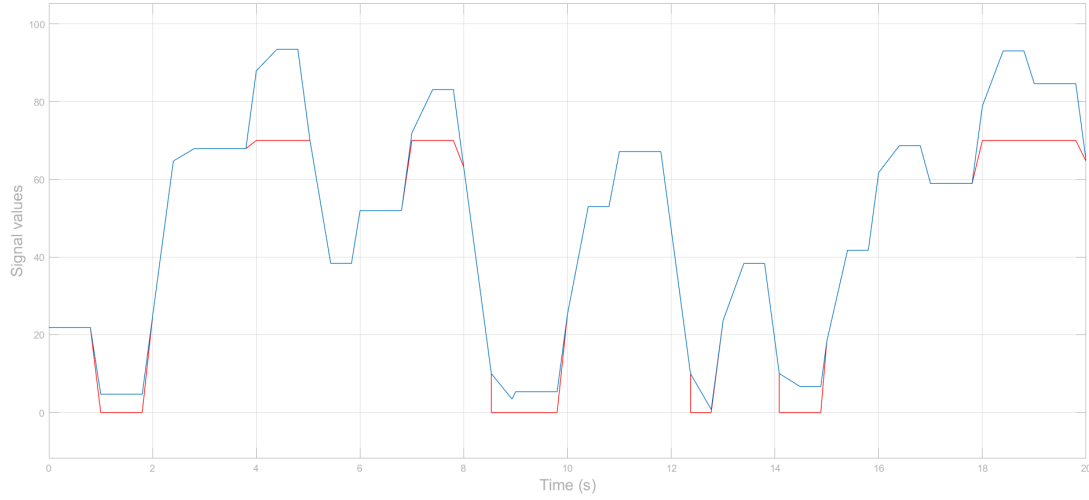


Figure 32: Result of the simulation (red) with input signal (blue)

These results also point to the possibility of making the whole circuit work, from the sensibility of the sensors to the transmission of the information to the user. The elements needed for this prototype to work are very small, lightweight and inexpensive, and they could be added to some low tech prosthesis.

4 DISCUSSION

As seen in the previous section, the results show that this model of tactile feedback, although crude, can work. The sensors are able to work in the needed range and the motors can convey the difference in information needed for telling apart light touch from hard grip, particularly when using different patterns of vibration instead of a continuous signal. These results, in addition to the simulation, suggest that a working prototype can be built with lightweight and inexpensive materials, which is the goal of this project. The last experiment shows that the user can understand the grip force exerted when the only feedback is tactile. This is a very important point in the process, as the whole system is based on this idea, and it goes in concordance with the findings of (Raveh et al., 2018a), who found that vibrotactile feedback is almost as good as visual feedback. In addition, the system can be individualized according to each user's needs, adding different patterns and levels of vibration according to their routine, needs and preferences. It's important to note that vibration might not be a suitable kind of feedback for every amputee that wants to have this feature added to their prosthesis, as vibration might be unpleasant for some people (Ko et al., 2015).

There is still much improvement that can be made in the prototype as the whole study had some limitations. The first one is the small pool of subjects, consisting of only one person with both hands. A larger pool is needed in order to be able to confirm that this is a suitable method for tactile feedback for a wide population, and find the statistical significance of the results. Particularly important is to perform the experiments with amputees. Some more experimentation with each subject to monitor their learning capability is also recommended, although the limited experimentation suggests that the process of learning is fast and intuitive, as presented in earlier works (Wijk et al., 2019).

In the last experiment another issue was also pointed out. This particular system with these sensors only work for small pressures or hard surfaces, and the results may vary if the objects picked are soft and need a higher pressure. This could be addressed by changing the sensors, but more experimentation with objects with different mechanical properties is recommended. However, the comparison between the expected and recorded results show a promising path for this particular system.

Other lines of future research might be how would having several signals at once affect the perception of the feedback in the user and if having very different settings for each finger would help in the learning process or if it would slow it down.

Another possible improvement is to create a better set of sensors by using molds with the fingertip shape before pouring the silicone. This would create sensors with smoother surfaces and more lifelike that could transmit the signals more reliably.

5 CONCLUSION

Each experiment was designed to answer a different question. The possibility of recording the needed pressures, the ability to differentiate continuous levels of vibration and the viability of the whole system for the intended purpose. The experiments resulted in different levels of success, the last one being the most successful and having the best equipment: barometric GY-63 sensors and coin vibromotors.

The results obtained in the experiments for the one case study point to the possibility of building a working prototype with the characteristics needed to give tactile feedback to a prosthesis user. The experiments prove the idea that tactile feedback can convey the information of different levels of pressure being applied by the prosthesis, and the user can adjust this pressure accordingly. It is important to point out that these pressure levels go in ranges, with no distinction made between the upper and lower limit of each range, so the levels at which to change the vibration patterns need to be considered carefully.

Overall, the findings suggest that this prototype could be built without a significant investment, and it could potentially help a portion of the population in need of such an upgrade in their prosthesis. For some low-tech prostheses, such as the ones built for children or the homemade versions for families with a low income, this kind of system could easily be added without the need for a big change in the design, making it readily accessible.

This system, in addition, can be easily individualized and customized and all of the elements can be found in any electronics component store.

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