Variable stiffness prosthetic grasper with myoelectric control
Final report

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Abstract

Motor impaired people in Bolivia represent a 10% of the country's population. Unfortunately, due to Bolivia's limited health care system they are not being taking care of.

Prosthesis that can give back the functionality of the lost member to the user are quite expensive and technologically unreachable in this part of the world. This is why we have developed a variable stiffness grasper controlled by myoelectric signals that could be part of a biomimetic prosthetic hand.

This project would allow us to give back the functionality of lost limbs to a number of people that otherwise can't afford the cost of this technology.

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Chapter 1

Introduction

Every year, the Robotics and Automation Special Interest Group on Humanitarian Technology (RAS-SIGHT) funds a few projects that aim to improve the quality of life of a targeted group.

Within this program framework, the team UoD and UPB presented a proposal that was granted 2500 USD in may 2017. This was the start date for the local development of a variable stiffness prosthetic grasper.

The UoD team is lead by Markus Pakleppa, PhD in Dundee Scotland. Markus worked with a couple of students of the Biomedical engineering Masters program: Phongpan Tantipoon and Thomas Doublein.

The UPB team is lead by Cecilia Tapia, PhD and Oscar Urqidi, MSc, in Cochabamba Bolivia. Cochabamba's team was completed with 4 electromechanical engineering students: Andrea Avila, Mayra Mamani, Dennis Arandia and Jorge Loza.

1.1 The problem

The most recent National Census of Bolivia (2012) revealed that there is a group of 340.000 handicapped people in the country [1]. Amongst them, 34 % have some sort of motor disability [2]. According to the WHO [3], these figures should be multiplied by 10 to adjust for the actual numbers.

Even though the cause of amputation can be quite different, figures are quite similar in other developing countries: Vietnam: 200 000 amputees, Cambodia: 36 000... [4]. The cause of amputation in these countries depends on their stage of development. Amputation in these countries can be the result of several facts: fighting and explosion is the first reason in war zones and post-war zones while traffic and work accidents are common cause in peace zones [4]. However, financing health services in these countries is one of the most controversial topics.

Due to the important number of amputation in these countries and the limitation of available facilities and poor health care systems [5], it is important to provide prosthesis which can be manufactured at low cost. This is why we propose a myoelectric controller which can be used in prosthetic hands for amputees in developing countries by using low-cost electromyography processing.

Worldwide prosthetics technology has evolved to the point of creating artificial limbs that have the same metabolic cost of the amputated limb [6], they can even induce the feeling of tactile feedback to the user [7].

Myoelectric signals of antagonistic muscles of residual limbs can be used to control prosthesis [8]. This technology is already commercially available, but its cost (from 15.000 USD to 50.000 USD) makes it unreachable for the average population. Unfortunately, and leaving aside the limitation of the price, in Bolivia the access to any "smart" prosthesis is very limited. Although we have volunteer centres that produce and coordinate the provision of prosthesis to the low income population, the need to develop technology that improves the functionality of those prosthesis is a concern of the above mentioned volunteer centres as well.

Although myo-electric prosthesis are in general an aesthetic option for hand prosthesis, and leaving aside the cost, they are not necessarily fully accepted. These devices may look more natural than the body powered hooks or hands, but they still lack the natural feedback feeling of the later. These are part of the reasons prosthesis rejection has a 20% rate of abandonment [9]

1.2 State of the art

Some of the most advanced prosthetic hands are SensorHand of Ottobock, the Bebionic hand of RSLSteeper and the I–limb of Touch Bionics, which made a big step forward in technology by adjusting the grip force based on slip sensing on the fingertips [10].

The prices of these products are not made public, but according to a BBC blog a bebionics hand was provided in 2015 to a patient for 45000 USD. These prices make it the sort of technology that is not accessible even for industrialized countries population.

Leaving the price aside, there is a wide variety of options for prosthetic hands that range from cosmetic prosthesis, body powered prostheses to myoelectric active prosthesis with tactile feedback that allows the user get the feeling of his fingertips [10]. This last is not yet commercially available.

Figure 1.1: OpenBionics ada hand v1.1. Extracted from OpenBionics Website: https://www.openbionics.com/

There are some initiatives to share the knowledge and the technology needed to build prosthesis at the cost of the materials only. For example, Enabling the future is a global network that shares knowledge about upper limb prosthetic devices. It is constituted by volunteers that create open source designs of prosthetic devices that can be downloaded and 3D printed anywhere in the world. (http://enablingthefuture.org/upper-limb-prosthetics/the-flexy-hand/). A similar initiative is OpenBionics (https://www.openbionics.com/) which has developed a hand printed with elastic filament (see Figure 1.1).

Body-powered prostheses are quite common, as their cost is relatively affordable compared to myoelectric ones. These prostheses use cables to link the movement of a part of the residual limb to the prosthesis to control it (See figure 1.2). Different movements will result in applying tension on the cable, which will cause it to open, close, or bend.

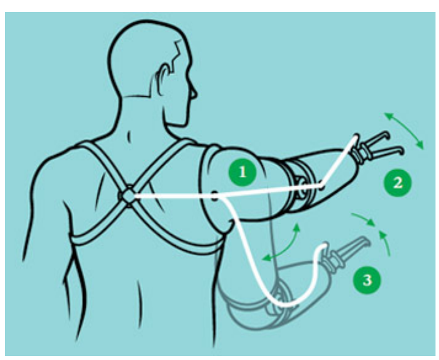


Figure 1.2: Mechanism of body powered prosthetic grasper. Extracted from Wired article: https://www.wired.com/2012/03/ff_prosthetics/

Motors and other actuators are used for active prosthesis, as when using myoelectric signals to control them. The movement of these prostheses can be controlled through the activation of some muscles that the user is trained to control for this purpose. These traditional actuators are traditionally stiff, and therefore the action over the object to grasp requires feedback to perform more natural grasping movements [10].

Traditionally stiff actuation performs a movement to a specific position which is then held regardless of external forces (within the actuator's range). In contrast, a variable stiffness actuator will deviate from its set point position to allow some smooth interaction with the object [11]. Variable stiffness actuators are recently getting attention from research groups around the world as they represent a suitable solution for the user–robot safe interaction [11].

Although myoelectric signals are being used to control prosthesis, we have no knowledge of a product using myoelectric control and variable stiffness for hand prosthesis. Most of the variable stiffness joints developed for prosthesis are used for knees or lower limb prosthesis.

1.3 The solution Proposed

Considering that a myoelectric hand is a more natural looking and *could be* a less exhausting device (electric motors assistance), but has a higher maintenance cost and complications (electrodes replacement, electronic parts), we have chosen to develop a device that can be body actuated and that can be used for a myoelectric version aswell.

Our team has been working on manufacturing of a variable stiffness joint with 3D printing technology. At the same time we have been working on myoelectric control for robotics.

Based on these two fields of work we propose to develop a grasper with variable stiffness controlled by arm movements (body powered) and another version controlled by myoelectric signals acquired on the forearm.

This grasper would be used to produce an active prosthetic hand, that could be manufactured anywhere a 3D printer is available. We propose to perform force control of the grasper to mimic natural movement and give the user a higher level of functionality than conventional or body-powered prosthesis.

As we have one of our teams working in Bolivia, we have planned to reach the affected population there by developing a prototype and sharing our knowledge to enable other groups replicating the prototype.

Chapter 2

Implementation of the Project

2.1 Project design: Objectives and Deliverables

Goal: The main goal of the project is to develop a grasper that allows the user to tune its stiffness to preform tasks with different levels of force.

Beyond this main goal, the project has a few secondary goals:

- Local development of devices to achieve some level of technological independence
- To develop a prosthetic grasper that can be easily manufactured
- To develop a cheap device

Objectives This project aims to achieve within 8 months of work and with the resources available:

- Design and development of a grasper of an adult human characteristics.
- Designa a development of a variable stiffnes mechanism, capable of controling the force in the grasper.
- Develop and build a working prototype of the variable stifness grasper.

Deliverables The deliverables defined within the project's framework are:

- Grasper

- Variable stiffnes mechanism
- proof of concept: working prototype
- Journal Publication
- Dissemination in local fairs and events

2.2 Project implementation - Timeline

We have divided the project in two stages, in terms of time and budget. The first stage would last 8 months and would finish in December 2017 with a working prototype and its usability test.

The time-line proposed and followed for this stage can be seen in Figure 2.1.

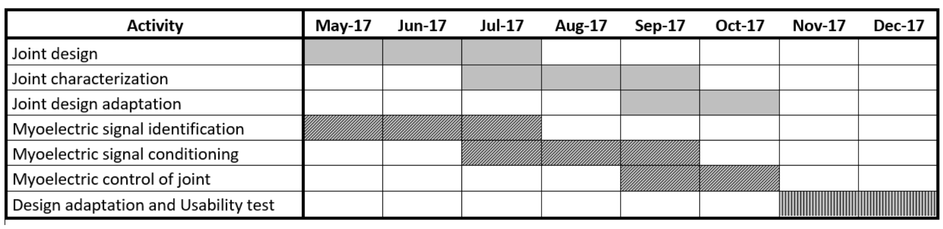


Figure 2.1: Project development time-line

2.3 Prototypes

2.3.1 First joint design

The first joint was designed to be fully manufactured by 3d printing. The prototype included a spring printed with elastic filament (Figure 2.2).

This first grasper used a standard servomotor (HITEC HS311)

Variable Stiffness Prosthetic Joint Characterisation

As part of this project we analysed the characteristics of the developed variable stiffness joint (UPB design). Using the design files of the UPB joint, a copy of it has been manufactured at the University of Dundee. The elastic spring was manufactured from flexible elastomer-based filament (NINJAFLEX 3D) while the remaining components of the joint were made from thermoplastic filament (2.85 mm Black PLA 3D Printer Filament). As

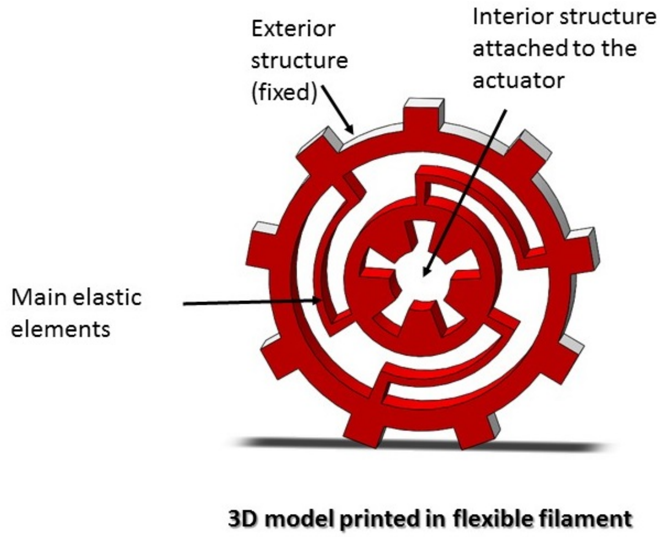


Figure 2.2: Spring printed in elastic filament. UPB design

Figure 2.3: Gripper components

shown in Figure 1, the manufactured joint was modified to allow its characterisation in an industrial tensile testing machine (Tinius Olsen H5KS).

Aim of the test was the evaluation of the stiffness control, in particular the controllability of the stiffness via the servo motors. Using a micro con-

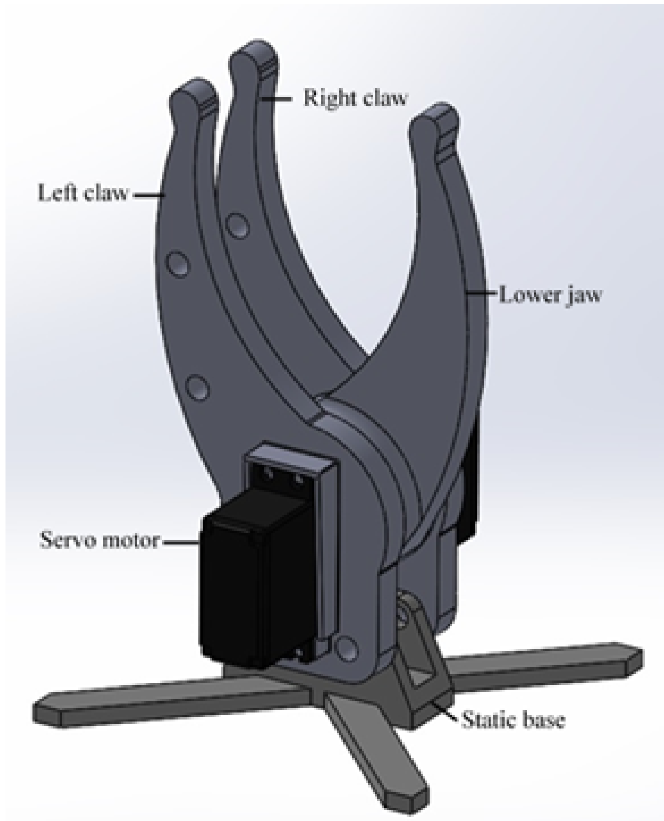


Figure 2.4: Gripper model assembling

troller (Arduino Mega 2560 Rev 3), the servo motors of the joint have been controlled to adjust the joint stiffness in various configurations. The setup allowed the control of the joint stiffness as well as the measurement of the stiffness using the industrial tensile testing machine. The stiffness of the joint k was analysed by relating the torque (τ) on the joint to the individual angular displacement (θ).

$$k = Fl/\theta \tag{2.1}$$

The stiffness was tested at multiple angles ($30^o, 35^o, 40^o, 45^o and 50^o$) of the servo horn and the experiment was performed over 3 repetitions (see Table 2.1). The statistical analysis of the results (one way ANOVA,$\alpha = 0.05$) has shown a significant difference ($p < 0.05$) in joint stiffness for servo angles in the range of $30^o - 50^o$.

The results indicates a that the stiffness can be directly controlled with

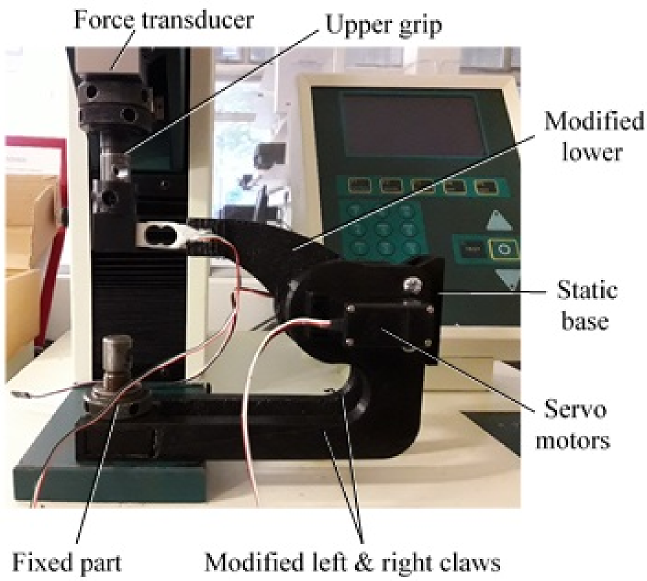


Figure 2.5: Test set-up used to characterise the UPB joint design.

Table 2.1: Results of joint stiffness characterisation

Servo position (Deg.)	**Stiffness (Nm/rad)**			
	1st Measurement	2nd Measurement	3rd Measurement	**Mean ± SD**
50	0.07	0.07	0.07	0.07± 0.00
45	0.15	0.21	0.21	0.19 ± 0.02
40	0.46	0.41	0.38	0.42 ± 0.04
35	0.76	0.66	0.73	0.72 ± 0.05
30	0.77	0.77	0.81	0.79 ± 0.02
p-value (one way ANOVA) * Level of significant at p < 0.05				0.000*

the external servo motors, or wires actuated by body movements. This would make the joint suitable for an application where the stiffness has to be adjustable.

2.3.2 Myoelectric Control

As part of the development of the myoelectric grasper we looked into the control of the joint using low-cost electronics. Rather than relying on individual hardware solutions we were interested in the application of microcontroller boards and sensor solutions that are more flexible and readily available. Through a series of experimental measurements of the electricity generated during muscle activation in different parts of the arm we analysed signals to relate them to grasping force and position of the arm. Aim of the project was the implementation of a myoelectric controller with the selected hardware (Bitalino Plugged Kit Bluetooth). The measurement hardware included the sensors as well as microcontroller board to acquire the myoelectric signals. Gelled self-adhesive disposable electrodes were used to measure the required signals on the participants of the study. Using a modified hand dynamometer (see Figure 2.6) we were able to measure the grasping force while also measuring the myoelectric signals. For the experiments, 17 healthy subjects

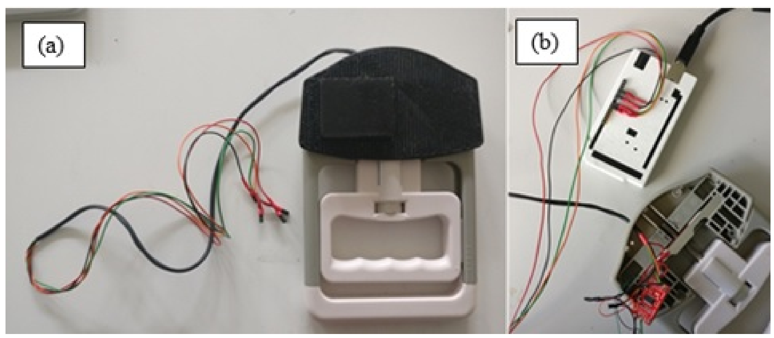


Figure 2.6: Hand dynamometer (a) with additional data acquisition hardware (b).

between (9 female, 8 male) 18 and 50 years old have been recruited. As shown in Figure 2.7, a set of electrodes was placed on the biceps and another set was placed on the forearm. Both electrode sets were connected in bipolar configuration on the volunteers' dominant arm.

Volunteers performed a set of tasks while the myoelectric signals and grasping force have been acquired. Participants were asked to angle their arm at 90 deg for 10 seconds before they were to relax it for another 10 seconds. This was repeated for different weights which were held by the participants (1kg, 2kg and 3kg). Subsequently participants were asked to grasp the hand dynamometer as hard as possible and hold this position. This was performed to find features in the myoelectric signal which could be related to the grasping force. Electromyograms have been acquired with a sampling frequency of 1000 Hz.

Once the experiments have been performed the data has been analysed to

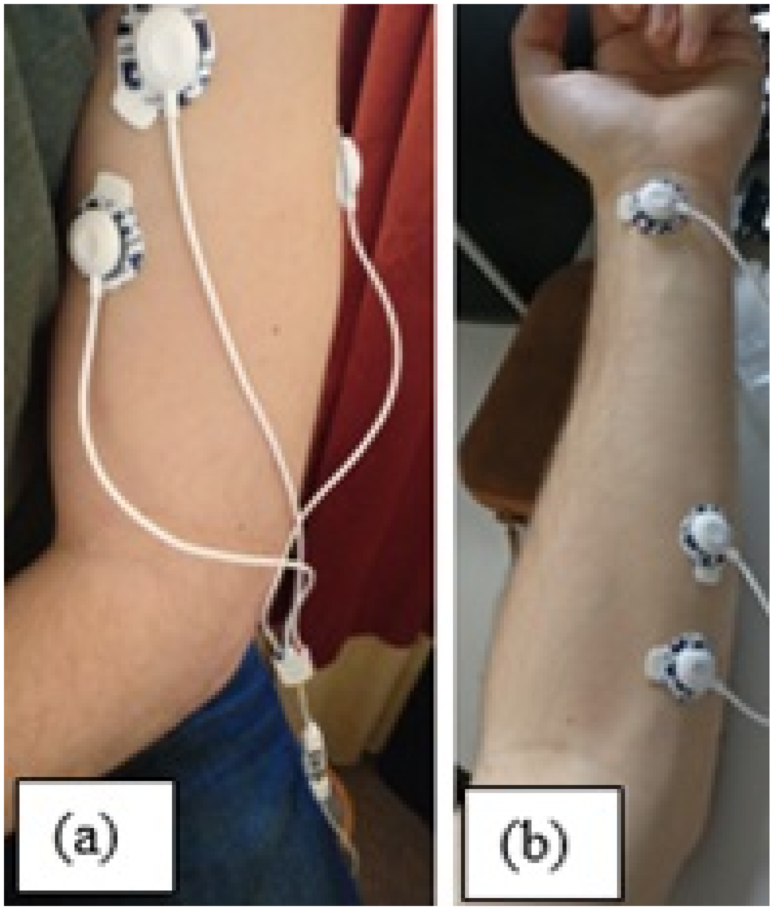


Figure 2.7: Electrode placement on volunteers (a: biceps, b: forearm).

derive features which would be usable for the control of the variable stiffness grasper. The frequency of the acquired signals was analysed to detect the contraction of the muscle based on a frequency threshold of 1 Hz. In order to control the stiffness of the joint we chose to also integrate the maximum amplitude of the acquired signals. This decision was made since the amplitude can be directly related to the grasping force which was also confirmed by our experiments. This relationship was observed by comparing the maximum force measured with the hand dynamometer with the maximum amplitude of the electromyogram. The ratio between the two values has shown no significant difference between subjects ($p > 0.05$, ANOVA,$\alpha = 0.05$) which indicates the suitability of the maximum amplitude of the electromyogram to control the grasping stiffness. The final controller design is illustrated in Figure 2.8.

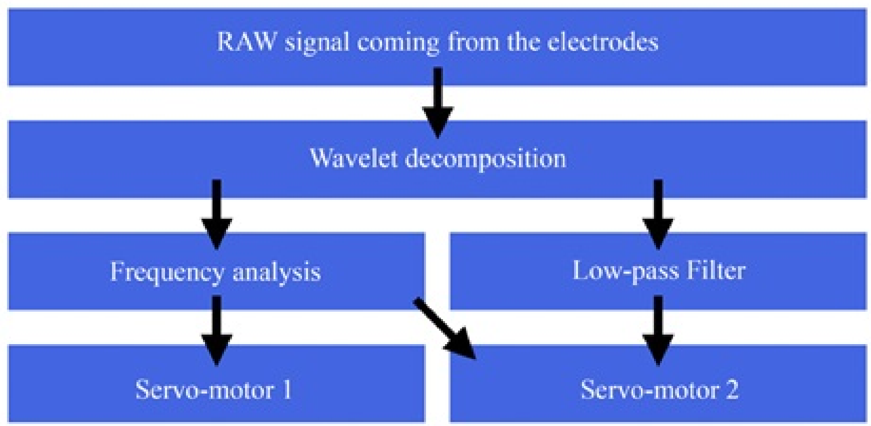


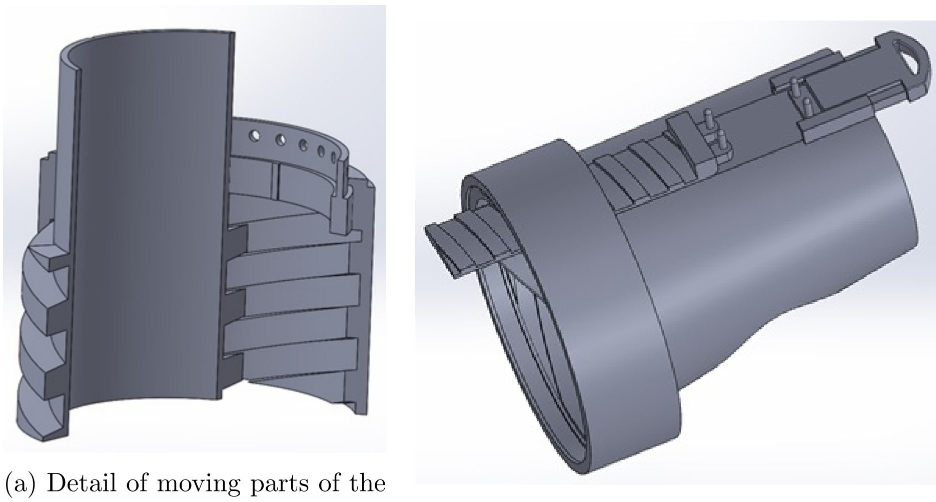
Figure 2.8: Schematic of the myoelectric controller.

The frequency threshold was detected to either open or close the grasper completely while the stiffness was adjusted by measuring the amplitude peaks of the signal. Activation of the muscle will close or open the grasper depending on its previous state. The amplitude is then used to adjust the position of one servo horn in the antagonistic servo configuration. This adjusts the stiffness of the spring.

An additional study will be required to test and improve the robustness of the controller since only a limited amount of results was acquired over the course of this project.

2.3.3 A body actuated hand

At the core of the project is the development of a fully mechanical body-actuated prosthetic hand. At first, the design process was based on open source printable models, looking for the addition of a way to regulate actuation stiffness. We built and evaluated some of these models; our analysis suggested that the models available were not suitable for our purposes. The main reason was the inherent stiffness of the joints and actuation mechanism, as well as its focus on giving a "natural look", aiming for an increased sense of acceptance and self-confidence by the user, but not taking functionality as the main factor.



(a) Detail of moving parts of the mechanism

(b) Assembled view

Figure 2.9: Forearm stiffness regulation mechanism

At this point we decided to start from the beginning and redesign the whole prosthetic hand, based on our needs. As a first stage of conceptual design, we focused on three main aspects: minimize energy loses in the actuation, allow grip stiffness regulation and provide an efficient way of mechanical actuation by the forearm and wrist.

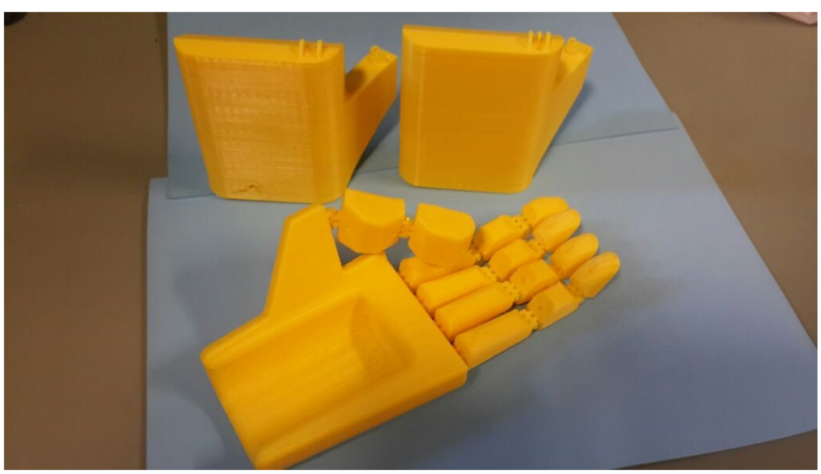


Figure 2.10: Test 3D printed hand palms and prosthetic hand assembled with fingers.

As shown by Figures 2.9a, 2.9b and 2.10, the basic design was proposed as a hand, composed of a palm and a group of compliant fingers, attached to a forearm clamp through two sets of tensors. Each set of tensors is designed to open and close the hand independently, although both sets are meant to work together in an antagonistic way (holding the position of the fingers). This feature allow stiffness regulation, since the stiffness of grip can be changed by adding or removing tension to the tensors (without affecting the force needed for actuation).

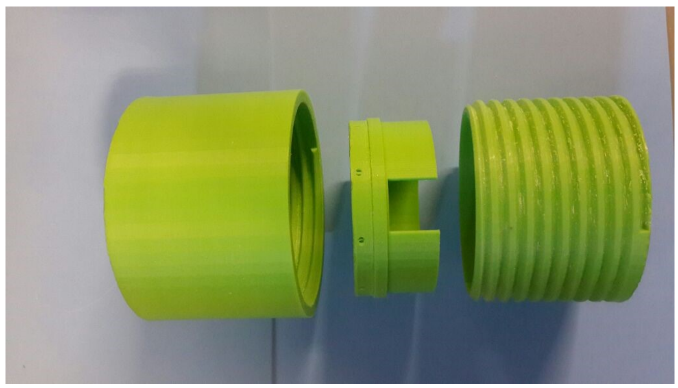


Figure 2.11: Adjustable forearm clamp system.

To achieve this last objective, it was enough to add an elastic characteristic to tensors; as springs or rubber bands. Regulation of tension is made by a clamp with a retractable system, capable of stretching the elastic tensors. With this system (shown in 2.11), the user can regulate the stiffness of its grip, depending on the situation.

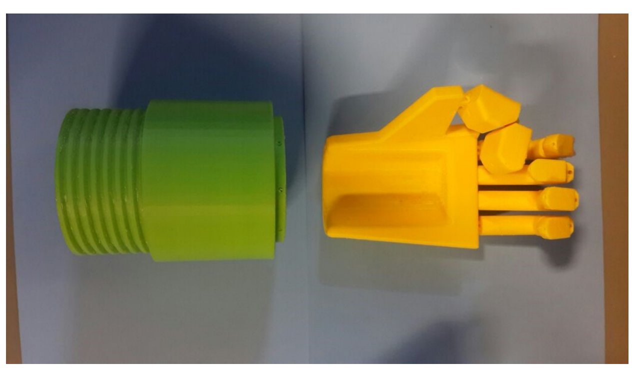


Figure 2.12: Main components of the system.

At first, a screw-nut linear system was proposed, but there are other configurations to be explored. The system shown in 2.12 was developed as a proof of concept. Further development is needed to achieve its fully functional state.

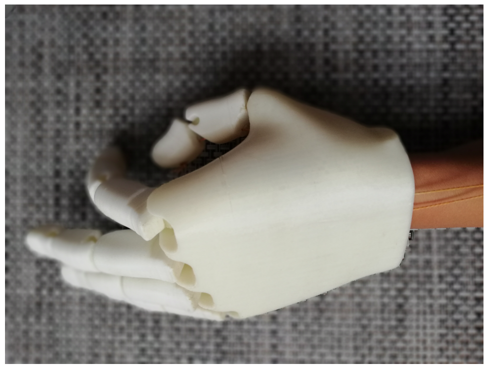


Figure 2.13: Hand with grasper closed.

This system allows the user to regulate the stiffness mechanically with one hand, and activates the grasper part (thumb and index) by moaking a movement with the wrist (Figure 2.13).

Figure 2.14: Prototype fully assembled.

The gap between the stiffness regulation part an the hand itself (Figure 2.14) has to be adequately regulate for each user, as the tension on the strings will give the initial stiffness of the device.

2.4 Budget

The R&D department at UPB has hosted our project and granted us some paid time to work on it. UoD team members have worked in a similar situation. Both R&D departments supported us with some material as well. We received 2500 USD from RAS SIGHT to complete the 1st stage of this project. This involved having a prototype ready by December 2107, leaving the community deployment for a second stage to be conducted in 2018.

For practical reasons the funds were delivered to UPB.

The materials used can be seen in table 2.2 As can be appreciated, the funds received covered completely the material we used. The remaining funds were used to co-finance, along with UPB funds, the purchase of a 3D printer (SLA FORM2) which costs 6500 USD delivered to Bolivia.

Once we receive it, this printer will allow to develop detailed prototype mechanisms and improve the inner channels for the wires and springs in the hand. Which are giving us some problems with our current 3D printer.

Table 2.2: Breakdown of anticipated costs of material in USD

Item	Quantity	Cost	Total
~~Micromotor w/encoder~~	~~3~~	~~500~~	~~1500~~
Standard servomotor	4	10	40
MyoWare Muscle Sensor Development Kit	3	100	300
Electrodes pack 10	50	8	400
3D printing elastic filament	4	30	120
3D printing standard ABS filament	3	30	90
3D printing standard PLA filament	*3*	*30*	*90*
Sensors	9	10	90
Total Materials			**1130**

Chapter 3

Results and Discussion

We have developed a grasper that allows the user to tune its stiffness. This grasper is body actuated, as we planned to have a version without any electronic part, to make it accessible and easy to maintain in rural areas. This prototype has 3 fingers that are completely passive, for the moment.

In the process we have designed a variable stiffness grasper that uses only 3d printing methods to be manufactured. Two different Myoelectric controllers have been developed as well. These controllers allow the use of standard servomotors to emulate a variable stiffness actuation. Although these controllers are not currently being used in the final prototype, they will be implemented in the next stage of the project.

This year we are planning to refine the prototype by giving movement to the 3 fingers that are not being used right now. We need to work on the material in contact with the skin and giving an second degree of freedom to the thumb, to give a wider span of action to the user.

3.1 Dissemination

3.1.1 Publications

VARIABLE STIFFNESS HAND PROSTHESIS: A SYSTEMATIC REVIEW, S. Cecilia Tapia-Siles, Oscar Urquidi-Gandarillas and Markus Pakleppa. INVESTIGACIÓN & DESARROLLO, No. 17, Vol. 1: 99 – 108 (2017) ISSN 2518-4431

3.1.2 Prize

The work done on myoelectric control of force was presented in a national fair of Science and Tecnology in Bolivia organized by the Science and Technology Vice-Ministry. During this event our project was awarded the 1st prize in its category.

3.1.3 Regional science fairs

The work done in this project was presented during the "EXPOCIENCIA" a regional science fair at the Gabriel Rene Moreno Unversity in Santa Cruz de la Sierra - Bolivia

3.2 Further work

During this project time we have developed only a prototype. We need now to fully adapt it to the persons who need it.

The next stage of this project involves development of the areas in contact with the skin of the user. Wee need to avoid slip in these areas as we are using the movements of the arm and wrist to control de hand. At the same time we should be careful to avoid irritation or any damage of the skin, caused by the device's use.

Summarizing our next steps will be:

- Develop layer of material in contact with skin
- complete the passive activation of other three fingers
- Add a degree of freedom to the thumb to increase the hand's range of actions.
- Test the device with volunteers who need this sort of device.
- Quantify and compare the use of this prototype with other open source devices.

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Appendix A

Publications and material generated during the project execution

The following poster was presented in the National fair ”Expociecnia” in Santa Cruz - Bolivia.

A.1 Review paper

INVESTIGACIÓN & DESARROLLO, No. **17**, Vol. **1**: 99 – 108 (2017)
ISSN 2518-4431

VARIABLE STIFFNESS HAND PROSTHESIS: A SYSTEMATIC REVIEW

PRÓTESIS DE MANO DE RIGIDEZ VARIABLE: UNA REVISIÓN SISTEMÁTICA DEL ESTADO DEL ARTE

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ABSTRACT

Prosthetics is an important field in engineering due to the large number of amputees worldwide and the associated problems such as limited functionality of the state of the art. An important functionality of the human hand is its capability of adjusting the stiffness of the joints depending on the currently performed task. For the development of new technology it is important to understand the limitations of existing resources. As part of our efforts to develop a variable stiffness grasper for developing countries a systematic review was performed covering technology of body powered and myoelectric hand prosthesis. Focus of the review is readiness of prosthetic hands regarding their capability of controlling the stiffness of the end effector. Publications sourced through three different digital libraries were systematically reviewed on the basis of the PRISMA standard. We present a search strategy as well as the PRISMA assessment of the resulting records which covered 321 publications. The records were assessed and the results are presented for the ability of devices to control their joint stiffness. The review indicates that body powered prosthesis are preferred to myoelectric hands due to the reduced cost, the simplicity of use and because of their inherent ability to provide feedback to the user. Stiffness control was identified but has not been fully covered in the current state of the art. In addition we summarise the identified requirements on prosthetic hands as well as related information which can support the development of new prosthetics.

Keywords: Hand Prosthesis, Prosthetics, Variable Stiffness, Compliant Joint.

RESUMEN

El estudio de prótesis es un campo importante en la ingeniería debido al gran número de amputados en todo el mundo y los problemas asociados. Entre estos problemas están las limitaciones en funcionalidad de las prótesis modernas. Una funcionalidad importante de la mano humana es su capacidad de ajustar la rigidez de las articulaciones dependiendo de la acción realizada. Es importante entender las limitaciones de los recursos existentes para poder proponer algún desarrollo tecnológico en el área. Como parte del trabajo para desarrollar una garra de rigidez variable para los países en desarrollo, se realizó una revisión sistemática de la tecnología que cubre las prótesis de mano mecánicas y mioeléctricas. El eje de esta monografía es la disponibilidad de prótesis de manos con respecto a su capacidad de controlar la rigidez del efector final. Se ha usado la metodología PRISMA para hacer una revisión sistemática de documentos obtenidos a través de tres bibliotecas digitales diferentes. Se presenta una estrategia de búsqueda, así como la evaluación PRISMA de los registros resultantes que abarcó 321 publicaciones. Se evaluaron los registros obtenidos y se presentan los resultados de la evaluación de la capacidad control de rigidez de los dispositivos. La revisión indica que las prótesis mecánicas son preferidas respecto a las manos mioeléctricas debido al coste reducido, la simplicidad de uso y sobre todo a su capacidad inherente para proporcionar retroalimentación al usuario. Se ha identificado el control de la rigidez en algunos registros, pero no se ha estudiado completamente en esta monografía. Finalmente, los requisitos del usuario para prótesis de manos han sido identificados, así como información sobre tecnología relacionada capaz de impulsar el desarrollo de nuevas prótesis que satisfagan estos requerimientos.

Palabras clave: Prótesis De Mano, Rigidez Variable, Articulación Flexible.

1. INTRODUCTION

The most recent national census of Bolivia (2012) revealed that there is a group of 340.000 handicapped people in the country [1]. Amongst them, 34 % have some sort of motor disability [2]. Although these are the official results of the Census, some programs on disability, such as the National Plan for Equality and Equalization of Opportunities

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(PNIEO), prefer to apply the 10% global average prevalence of disability established by the World Health Organization (WHO)[3].

Worldwide prosthetics technology has evolved to the point of creating artificial limbs that have the same metabolic cost of the amputated limb [4], they can even induce the feeling of tactile feedback to the user [5]. Although technology has evolved trying to restore the functionality of a lost limb, there is a large number of people abandoning their prosthetic upper limbs [6] [7]. Modern hi-tech prosthesis are expensive and not necessarily cover basic functions required by the individual needs [8]. There is a noticeable preference of body-powered prostheses over myoelectric prostheses due to cost, durability, ease of use, and direct force feedback [7][9]. Grasping force control and finger stiffness is important for daily tasks, but is not necessarily taken care of in commercial devices, it comes as a result of position or velocity control [10]. The ability of current upper limb prosthetic technology regarding their ability to regulate grasping stiffness is unclear. Therefore a systematic review was performed to determine the state of the art of variable stiffness applied to prosthetic hands or terminal devices.

2. HAND PROSTHESIS OR TERMINAL DEVICES

The human hand has 24 degrees of freedom, in a volume of 500 cc, or less, and a weight of less than 500 grams [11]. An artificial hand with that weight is perceived as heavy by the user. The weight of the prosthesis is causing pressure on a small skin area, causing discomfort and even damaging it.

A prosthetic hand is the terminal device or the end effector of upper limb prostheses. In terms of actuation, it can be body powered or externally powered. In terms of morphology it can be a hand, a hook or a special terminal device or attachment for specific tasks, like sports devices or work tools.[9] The standard upper limb prosthesis is body powered. It is still similar in concept to the Ballif arm. The Ballif arm dates from 1812 and uses the principle of a shoulder or arm movement to control the terminal device[9].

Body powered devices are generally operated by cables and springs. The cable, controlled by a harness on the shoulder and passed along the elbow, acts in one direction and the spring in the opposite direction. This means that a terminal device can be Normally Closed (NC; Voluntary Opening, VO) or Normally Open (NO; Voluntary Closing, VC). The VC device type is inspired by the human hand movements; it usually has a cam lock mechanism to keep it closed to avoid the continuous pull needed to hold an object. In contrast, the VO mechanism, is not as natural as the VC one, but requires an effort only to open it as the spring will exert the force on the object to be hold. Split hooks are usually VO, and tend to be preferred when functionality is more important over aesthetics. These are considered to be counterintuitive and so the force feedback can be confusing for the user.

Externally powered prosthesis have been proposed in the late 1950's to assist high level bilateral amputees [9]. They have evolved to become very sophisticated robotic devices, usually controlled by myoelectric signals and with a wide variety of feedback mechanisms.

The scope of this review covers body powered as well as externally powered devices, but it will be focused on hands or terminal devices and related technology.

3. METHODS

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA -P) method [12], has been chosen to conduct this review with an unbiased and organized approach. Technology Readiness Levels (TRLs) [13] have been used in order to assess the level of development of the devices found by the PRISMA-P methodology.

3.1 PRISMA –P METHODOLOGY

The PRISMA-P methodology proposes an evidence-based methodology for systematic reviews and meta-analyses. Although this system was initially proposed for health care reviews, it has been found very useful as a basis for reporting systematic reviews of technical research as well.

The PRISMA methodology suggests the description of all the information sources and the presentation of the full electronic search strategy of at least one database, in order to make it repeatable for the reader. It also requires to state the process for selecting studies and to describe methods of data extraction from reports.

3.2 TRL ASSESSMENT

Technology Readiness Levels (TRLs) are a system used to identify the level of technological maturity of a device. The system was invented by NASA's researcher Stan Sadin in 1974. It was formally defined by 7 levels of technology readiness in 1989. The present system uses a 9 level scale, where TRL1 indicates that an idea is being implemented in a practical application, based on observations of basic principles. The highest level (TRL9) identifies technology that has been fully incorporated into a larger system and is considered operational. [13]

This system was meant to identify when a device was ready to be part of a real space mission. Nowadays, the system has proven to be so useful in different fields like the oil and gas industry and not only in aerospace applications. For example, the biggest EU Research and Innovation programme, Horizon 2020 (H2020), is using TRLs to specify the scope of activities in projects they fund. Although the concept for different fields is similar, the definitions of each level vary according to the applications, and therefore Horizon 2020 has added a TRL 0 that identifies an idea or unproven concept, where no test has been performed yet.

The definitions used in this paper (see TABLE 1) correspond to the definitions of the EU Research and Innovation programme Horizon 2020.

TABLE 1 - TRL DEFINITIONS USED IN THIS REVIEW

TRL	Definition
0	Idea. Unproven concept, no testing has been performed.
1	Basic research. Principles postulated and observed but no experimental proof available.
2	Technology formulation. Concept and application have been formulated.
3	Applied research. First laboratory tests completed; proof of concept.
4	Small scale prototype built in a laboratory environment ("ugly" prototype).
5	Large scale prototype tested in intended environment.
6	Prototype system tested in intended environment close to expected performance.
7	Demonstration system operating in operational environment at pre-commercial scale.
8	First of a kind commercial system. Manufacturing issues solved.
9	Full commercial application, technology available for consumers.

3.3 ELIGIBILITY CRITERIA

The data and devices included in this article have been reported in scientific literature. They have been identified by searches in PubMed, IEEE Xplore and the ASME digital Library. The articles selected had to present work on prosthetic hands, prosthetic upper limbs, variable stiffness hands, reviews about these subjects and technology related to these devices.

3.4 EXCLUSION CRITERIA:

Amongst the papers retrieved some subjects that were irrelevant for this review had to be filtered. Some of the subjects excluded were:

- Prosthetic lower limb
- Prosthetic larynx
- Electrostimulation of muscles
- Implants
- Models of prosthetic implants
- Neuroimplants
- Magnetorheological fluids
- Crown cementing for divers

- Rehabilitation
- Exoskeleton (assist devices)
- Biomechanical study of motion
- Haptics for augmented reality

3.5 Information Sources

Scientific article databases were used to perform a systematic search of selected terms. Main databases were identified in the medical field (PubMed) as well as the main engineering ones (IEEE Xplore, ASME digital Collection).

3.6 Search Strategy

The search strategy was defined according to the main question of this review: Is there any prosthetic hand with the ability to regulate grasping stiffness? The full search strategy is summarised in TABLE 2 for the IEEE Xplore database, including the number of records found in each search performed.

TABLE 2 - SEARCH STRATEGY AND RESULTING RECORDS (FOR IEEE XPLORE)

			AND	AND	# of records
Subject headings + text words		Prosthe* hand	stiffness		40
	OR			modulation	3
	OR			control	35
	OR			grasp*	19
	OR		force	grasp*	181
	OR			modulation	14
	OR			control	296

4. CLASSIFICATION OF RECORDS

The records assessed were classified according to the technology used, as can be seen in Figure 1.

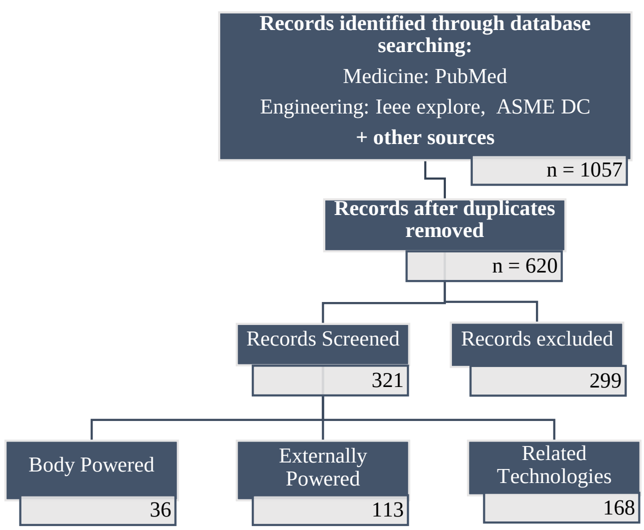

Figure 1 - Classification of records retrieved.

The technology readiness assessment was performed only on the most relevant records. An extra classification level was introduced where each group, Body Powered and Externally Powered, was subdivided in passive or active control of the device stiffness. The TRL level reached by each device, as well as the supporting information used to classify it, can be seen in Table 3.

TABLE 3 - TECHNOLOGY READINESS LEVELS OF SELECTED RECORDS

			Levels	TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
			Supporting information	Published research identifying problem/possible technology	Publications of analytic studies. Supporting analyses providing scientific information and data to develop research proposals	Proof of concept in lab, publication of results	Proof of concept and safety demonstrated in lab setup	Proof of concept and safety demonstrated with target subjects	Trials conducted in small number of humans	Safety and effectiveness trials in operational environment.Final design validated. SHAP or BBT	Available to the public (to be sold or reproduced (open source))	The device is being marketed/produced (open source). Post marketing studies
Body Powered	Control of Stiffness	Passive	Hosmer hook	Commercially available, SHAP 66, website (500 -900 USD)								
			LAVAL Underactuated [Laliberte2010] [Baril2013]	Prototype described in paper [Baril2013] preliminar SHAP								
			DELFT Cylinder Hand [Smit2015]	[Gemmell2016]: Tests in 13 able bodied subjects+ isolated tests with amputees								
			APRL [Gemmell2016]	[Gemmell2016]: Capstan to lock grasping posture								
			DELFT Stiffnes compensation, Wilmer group [Tolou2012], [Visser2000]	Concept and theoretical model and analysis presented [Tolou2012]								
			DELFT Force-Directed Design [Visser2000]	Lab prototype descibed in paper [Visser2000]								
			HYBRID VO-VC [Sullivan2011]	Lab prototype descibed in paper [Sullivan2011]								
			COIMBRA 3D Printed [Tavakoli2013]	Lab prototype descibed in paper [Tavakoli2013]								
		Active	Wrist [Montagnani2013]	Only Wrist, compliant, stiffnes controlled								
Externally powered	Control of Stiffness	Passive	Bebionic [Bebionic2003]	Widely commerciallized, website								
			I-limb Touch bionics	Widely commerciallized, website								
			SSSA-MyHand [CONTROZZI2016]	Funtional rototype presented [CONTROZZI2016]								
			TACT LOW COST HAND [SLADE2015]	Funtional rototype and open source design avalible[Slade2015]								
			Gas actuated arm [Fite2008]	Prototype evaluated in paper [Fite2008]								
			MULTIFUNCTIONAL HAND[WISTE2009]	Funtional rototype descibed in paper[Wiste2009]								
			RII Hand [Xu2015]	Prototype built and tested in experimental setup								
			SRIFFNESS DETECTION [ANDRECIOLI2010]	Control scheme and formulations presented [ANDRECIOLI2010]								
			Mesofluidic finger [love2010]	Finger with antagonistic actuators								
		Active	Takaki [takaki2011]	Robotic hand with force control on grasping [Takaki2011]								

5. RESULTS

Based on the previously introduced methodology we retrieved a set of publications which we subsequently analysed regarding their technical readiness in particular with a focus on variable stiffness. In addition we review the available means of actuation in current hand prostheses as well as their functionality.

- **UNDERACTUATION**

Underactuation is a desirable characteristic in a well-designed hand. Fewer actuators than degrees of freedom mean self-adaptability of fingers. In consequence underactuated grippers can have shape adaptation and therefore improved grasping capabilities as described in [14],[15].

A prosthetic hand with one externally powered actuator, could as well be body powered [16] [17] as the degrees of actuation are low. Nevertheless, effective underactuated prosthetic gripper with shape adaptability and low complexity is still a challenge.[14]

- **FUNCTIONALITY**

The I-limb, from Touch Bionics (Livingston, United Kingdom), provides different grip profiles that can be activated by the user [18]. It also offers additional Bluetooth devices, so called grip chips, which can be attached to an object in order for it to be recognized automatically by the hand, which in turn automatically selects the adequate grip profile.

The Bebionic hands, developed by RSL Steeper (Leeds, United Kingdom) and recently purchased by OttoBock (Duderstadt, Germany), as well as the Michelangelo hand (OttoBock; Duderstadt, Germany) both show a natural movement and a set of different grasping and holding functions. The user has to learn the usage of these functions first, as their control requires the activation of specific muscles in a certain pattern [19].

The Delft Cylinder hand is a hydraulically body powered hand. It provides a fully articulated hand at a low weight (273 g). The hand has two grasp patterns, namely precision grip and power grip. It has an underactuated adaptive structure that requires one control signal [20][21]. As it is body-powered it provides the user with proprioceptive force and position feedback without additional sensors.

Out of the 312 selected records a total of 113 publications focussed on mechatronic prosthesis. Most of the mechatronic devices are controlled by myoelectric signals. The “Multifunctional Hand” can be used with a multi-channel myoelectric interface. It represents a complex design with 16 joints and 5 independent actuators [30]. Amongst the myoelectric group, the “TACT HAND” is a low Cost 3D printed Myoelectric Hand. It is targeted at the low income population of developing countries, trying to achieve a performance comparable to hands “two orders of magnitude more expensive”. The open source design files are available online, and as it uses off-the-shelf electronic components and 3D printed parts it represents an affordable option anywhere the technology is available [31].

The SSSY-MyHand works with only 3 electric motors. It is comparable to the human hand in weight and is capable of performing most grasps and gestures used every day [33].

- **STIFFNESS CONTROL**

The control of the end effector stiffness has been identified as a need, unfortunately the problem is not yet solved by current devices [10]. The following section summarises the current state of the art and advancements regarding the implementation of stiffness control as well as related technologies.

Body powered prosthesis provide inherently uncontrollable end effector stiffness due to the currently used prehensor spring. The body joint, which actuates the effector, can actively control the stiffness in one direction depending on the user input. The resulting stiffness of the end effector is therefore a combination of the prehensor spring stiffness and the current state of the body joint. In myoelectric prosthetic hands the stiffness is not user controlled, but is a function of the implemented end effector velocity control or force control, or a combination of both.[10]

Low end effector stiffness has shown to improve the user’s perception of the object stiffness in body powered devices [10]. Therefore adaptive fingers with low stiffness have been used [22] for a prosthetic hand. The problem of added stiffness giving confusing feedback to the user has also been addressed by means of negative stiffness for glove stiffness compensation [23].

Stiffness detection is important for adaptive force control. The benefits obtained would be improvements in system response and reduction in oscillatory behaviour [32].

A passive compliant wrist has been introduced in [24]. The authors had observed that rigid wrists in prosthetic arms are the cause of strain injuries in the sound arm, because the users are leaving aside their rigid wrists prosthesis. The control of the stiffness, even if it is just switching from stiff to compliant, is shown to be fundamental in these cases. Another solution to the rigid wrist problem is adding an extra actuator for the wrist activation [25].

Although it is not addressed specifically as stiffness control, a gas powered arm with compliant hand joints: has been proposed in [26]. The passive means of switching between motion and force control without extra sensors or actuators has been proven to be a reliable mechanism [26].

Underactuation and compliance are being exploited for grasping improvement, using the adaptability of the shape of the compliant hand. An underactuated five-finger hand has been proposed and showed to be an effective technique to grasp small, circular and heavy objects. The forces of the action represent a human like force distribution. The simplicity of compliant Joints, in underactuated hands allow to have a design for single actuation source [27]. This means that it can be easily body powered or motor actuated. The COIMBRA 3D printed hand, presents compliant joints as well. It has a bio-inspired design, with soft fingers that can perform 23 of the 33 grasps that humans perform [29].

a. ASSESSMENT OF THE CURRENT SITUATION

We found several bodies powered and externally powered devices in TRL 9, but none of them have an active method of controlling the stiffness of the fingers or the grasper.

Technology of body powered devices seems to have been pushed aside by myoelectric devices. Nevertheless, it is important to highlight the needs of the end user of the device and the functional requirements identified in the works reviewed [7]–[9], [34]. One of the desired requirements on a prosthetic hand is the feedback to the user as this enables a higher degree of control over the hand. As part of this we saw various efforts to provide feedback with externally powered devices [35][36][37]. Nevertheless, body powered devices are still outperforming the externally powered ones in this aspect, as they give a natural feedback of the force applied, by the tension applied to the wires controlling it.

In terms of weight, the situation has not changed much in the last years. In 1998 Doshi's body powered hand [38] was 203 g. Today's mechatronic devices are within a range of 350 to 615 g in commercial prostheses and 350 to 2,200 g in research-based hands[19]

TABLE 4 - HIGHER TRL DEVICES AND THEIR FUNCTIONALITY

		challenge	force control	grasping	holding	lightweight	ease of use	cost	maintenance	stiffness feedback	aesthetics
TRL 7-9	9	Bebionic	×	✓	✓	×	✓	×	×	×	✓
	9	I-Limb	✓	✓	✓	×	✓	×	×	×	✓
	9	Hosmer Hook	✓	✓	✓	✓	✓	✓	✓	✓	×
	7	Laval Hand	✓	✓	✓	✓	✓	✓	×	✓	✓

b. IDENTIFICATION OF TECHNOLOGY RELATED TO HAND PROSTHESIS

Some records identified by this systematic search were not specifically reporting on hand prosthesis, but provided useful knowledge and methods which can benefit the development of these devices. The relevant information extracted from those records is presented in this section.

It has been detected that the glove used in many anthropomorphic hands, adds some stiffness to the prosthesis. In that sense, when the device is body actuated, this stiffness gives a confusing feedback to the user. The University of Delft has proposed a negative stiffness mechanism in order to compensate for the parasitic glove stiffness [23]. They have proposed a body-actuated design by considering the desired finger force distribution as a starting point. Clamping of the object is one of the most important aspects. "The way the hand moves to grasp an object should be such that it ends up in a good grip." [22]

Normally open hands need a continuous tension to hold an object. The APRL hand, amongst others [39] [40], has solved this issue by introducing a locking mechanism. It has a capstan to hold the grasping position on this NO hand [41].

The HYBRID VO-VC hand, presents a mechanical design that allows the user to change the configuration of the hand from Voluntary Opening to Voluntary Closing. It has been observed that VO and VC need to be combined to augment the system capabilities for daily tasks and work related tasks [28].

A nitinol rod is used to control the activation of the fingers in an underactuated hand [17]. It is not used as actuator but as a passive backbone because of its mechanical characteristics. The device uses only one motor for the actuation of the prosthesis.

It has been identified that low stiffness in a prosthetic hand provides a straightforward feedback to the user depending on the grasped object stiffness. Takaki *et al*. [42] have developed a robotic hand that uses low force to identify an object and then switches to high force to grasp it. This is a functionality that could be implemented in hand prostheses.

As mentioned before, the weight of the prosthesis is a very important characteristic. A way to distribute the weight or apply it to the rigid parts of the human body is Osseointegration. This is an invasive technique in which a titanium structure is attached to the bone to provide a mechanical interface. This way excessive pressure on the amputee's skin can be avoided, but as it is a very invasive procedure it can carry complications. [43]

c. IDENTIFIED REQUIREMENTS

Amongst the devices reviewed in this paper not a single device was identified that would completely meet the user requirements.

There are several works trying to identify the needs and wishes of the user [7], [8], [34]. Those studies highlight three important aspects: Cosmetics, comfort and control.

Cosmetic requirements are met by the use of special gloves that give a natural look to anthropomorphic prosthesis (basically all of the devices classified under externally powered). Unfortunately, and although they are widely used, split hooks remain quite visually unnatural.

Comfort requirements refer mainly to the weight and holding mechanism. In that sense, myoelectric devices rank lower than body actuated, as the harness used for the body actuated ones allows the redistribution of the weight and contact interface with the prosthesis.

Control requirements are closely related to task specific needs of the user, depending on the individual application in daily life.

These requirements have been expanded after an analysis of the main challenges faced by R&D departments to the date. The challenges identified are: force control, grasping functionality, holding functionality, lightweight, ease of use, cost, maintenance, stiffness control, feedback and aesthetics. A classification of the highest TRL records, showing which challenges have been completed, is shown in Table 4.

6. CONCLUSIONS

Body powered prosthesis are preferred to myoelectric devices due to their associated cost, simplicity of use but most of all, because they provide a natural feedback to the user [8].

Stiffness control or at least regulation has been identified as a need but has not being fully covered, even disregarded [10]. Stiffness of human fingers has been analysed by experiments which led into models [44]. This work can be beneficial for future work on variable stiffness end effectors.

More work needs to be done on body powered prosthesis, as they seem to be the preferred ones in terms of functionality, cost and ease of use.

7. ACKNOWLEDGEMENT

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A.2 Project poster

Diseño, construcción y validación de un sistema de control mio-eléctrico para garra con fines prostéticos

Andrea Avila Salvatierra, Cecilia Tapia Siles

Universidad Privada Boliviana (UPB)

PROYECTO GANADOR DEL **1º LUGAR** DE LA IV VERSIÓN DEL

PREMIO PLURINACIONAL DE CIENCIA Y TECNOLOGÍA 2017

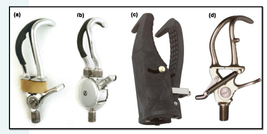
CATEGORÍA: **"Tecnologías de Información y Comunicación"**

INTRODUCCIÓN

Fuente: Instituto Nacional de Estadística

La tecnología ha evolucionado al punto de crear miembros artificiales que tienen el mismo costo metabólico del miembro amputado [4]

Pueden inducir la sensación del tacto en el usuario [5]

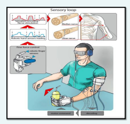


Discapacidad en Bolivia

El CENSO Nacional de Bolivia (2012) reveló que tenemos un grupo de 340.000 personas discapacitadas en el país[1].

34 % de ellos tiene algún tipo de discapacidad motora[2].

Según la OMS [3], y tomando en cuenta otros tipos de discapacidad no incluidas en las preguntas del censo, la cifra podría llegar a multiplicarse x 10.



Estado del arte

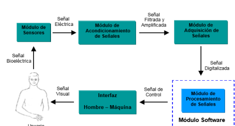
Aceptación/rechazo de prótesis

Las prótesis de miembro superior no son completamente aceptadas (estética, funcionalidad)

Se estima que existe un 20% de abandono de prótesis por estos motivos [6]

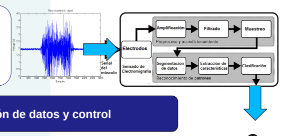
DISEÑO Y DESARROLLO

Esquema de control

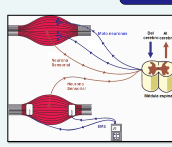


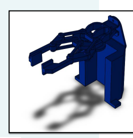
El Sistema emula un Sistema de control en fuerza.
El control en Fuerza otorga dentro del sistema la posibilidad de regular la velocidad y la fuerza con la que se desea realizar el movimiento, siendo este, de una forma natural, mucho más próxima a la de un brazo humano.

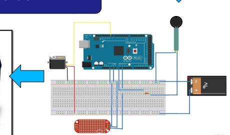
El dispositivo de control censa la señal mio-eléctrica del biceps en mV.
Esta señal proviene de las motoneuronas que activan una fibra muscular voluntariamente.



Adquisición de datos y control







RESULTADOS

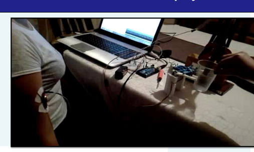
Análisis de correlación cruzada

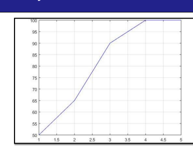
Correlación entre sujetos	Valor	Fuerza de Relación
Bajo – Medio	-0.340	Moderada
Bajo – Alto	-0.241	Débil
Medio - Alto	0.641	Fuerte

Se tomaron muestras de señales mio-eléctricas a 10 sujetos de distinta constitución física.
Cada sujeto levantó cíclicamente pesos de 1,2,3 y 4 kg
Estos datos se procesaron estadísticamente para determinar la importancia de los diferentes parámetros en el control mio-eléctrico desarrollado.

En base a los resultados de las señales adquiridas se desarrolló un sistema de control usando los niveles de activación mio-eléctricos mas estables detectados.
Este sistema permite la regulación voluntaria de la fuerza de la pinza mecatrónica controlada.
Se realizó la integración de un Sistema de control en lazo cerrado, mediante un sensor de fuerza que permite la asistencia en la tarea de sujeción de objetos.
La curva de aprendizaje promedio muestra que su uso es factible y fácil de dominar.

Prototipo y curva de aprendizaje





CONCLUSIONES

- *Los sujetos de desarrollo de músculo alto como los de desarrollo de músculo medio tienen la capacidad de aprender a tener conciencia de la intensidad de la contracción de su músculo por lo que se puede desarrollar un sistema de control en fuerza a partir de estas señales.*
- *Este sistema es especialmente interesante en el caso de niños que necesitan el reemplazo periódico del hardware, al crecer sus huesos con la edad. Este escalamiento, se hace relativamente simple al usar tecnologías de fabricación por adición de material (impresión 3D), comunes y accesibles en nuestro medio.*

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EXPOCIENCIA, SANTA CRUZ 2017

A.3 Presentation

Introduction

- Bolivian 2012 National Census:
  - 340.000 handicapped people[1].
- 34 % motor handicap[2].
- WHO: Motor impaired people in Bolivia represent a 10% of the country's population [3].
  - Due to Bolivia's limited health care system they are not being taking care of.

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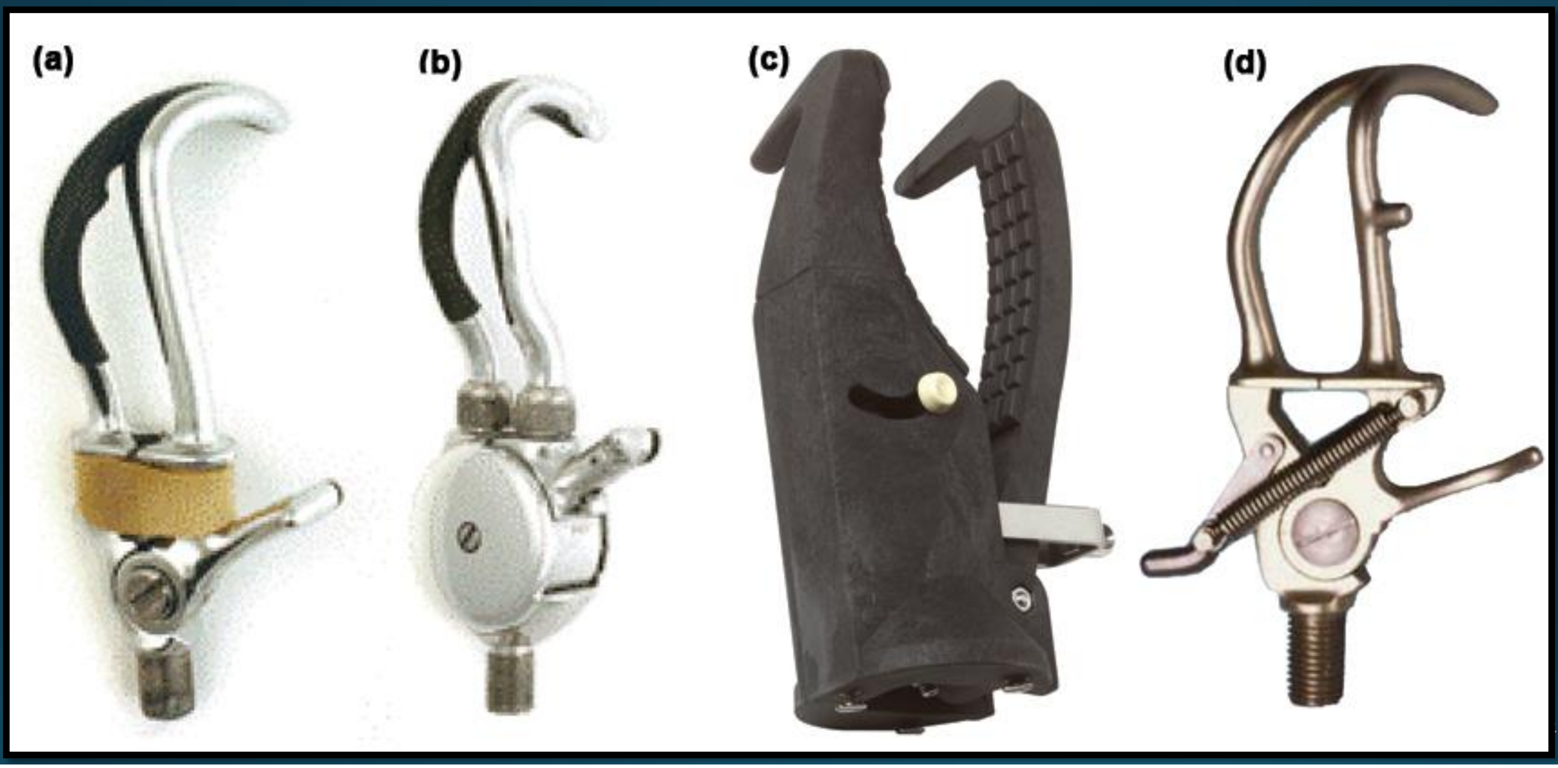
Introduction



→ 20%

.007.

Goals

- To locally develop a variable stiffness grasper.
  - To be implemented in a body powered prosthesis and myoelectric devices.
- Transfer the technology to a local charity foundation that builds prosthesis for low income people.

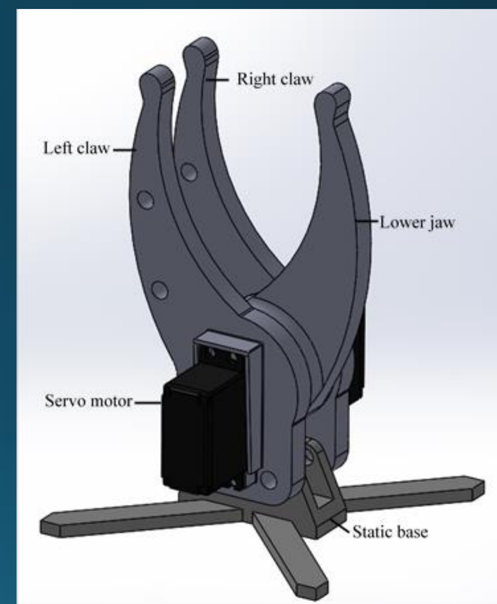
Project Timeline

Activity	May-17	Jun-17	Jul-17	Aug-17	Sep-17	Oct-17	Nov-17	Dec-17
Joint design	■	■	■					
Joint characterization			■	■	■			
Joint design adaptation					■	■		
Myoelectric signal identification	■	■	■					
Myoelectric signal conditioning			■	■	■			
Myoelectric control of joint					■	■		
Design adaptation and Usability test							■	■

Joint design V1

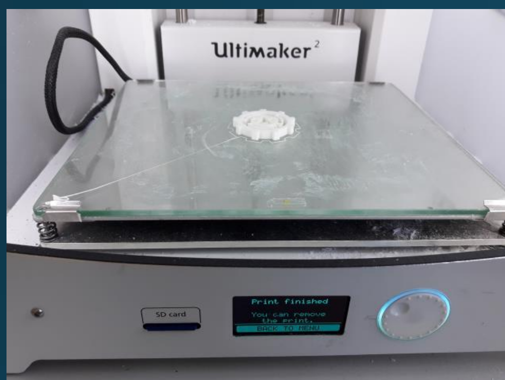
Spring component

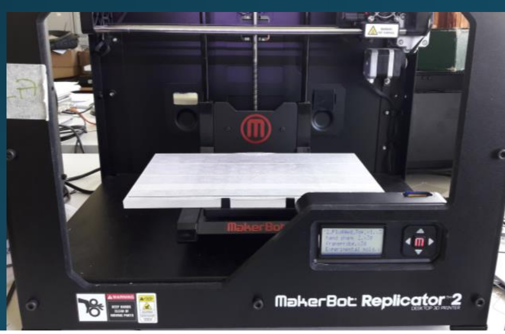
Gripper components



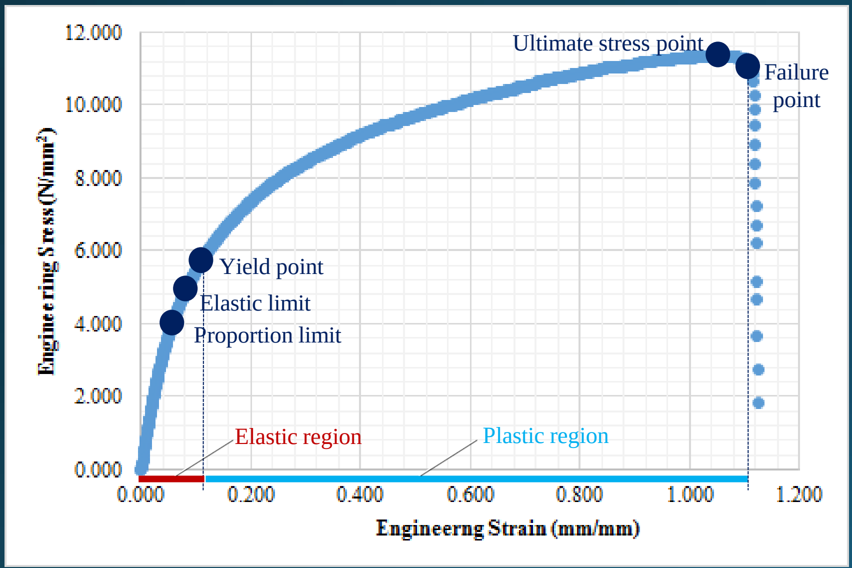
Gripper model assembling

Joint characterization

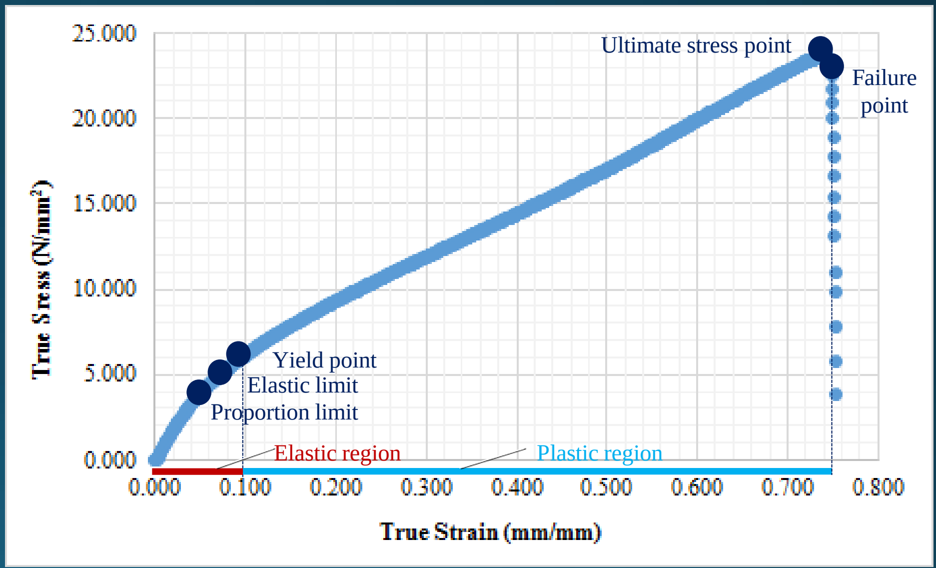




Stress strain Curves



Engineering Stress - strain

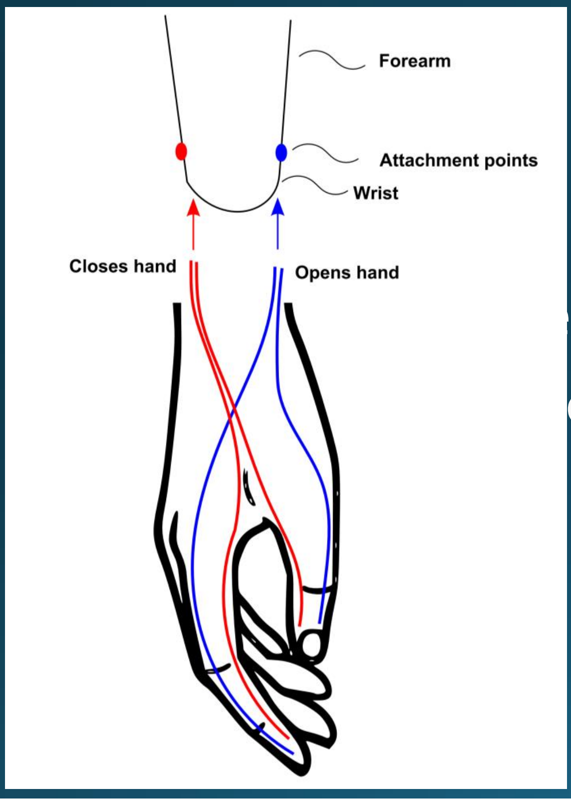


True Stress - strain

Outcome

- Publication:
  - TAPIA-SILES, S. Cecilia; URQUIDI-GANDARILLAS, Oscar and PAKLEPPA, Markus. VARIABLE STIFFNESS HAND PROSTHESIS: A SYSTEMATIC REVIEW. Inv. y Des. [online]. 2017, vol.1, n.17, pp. 99-108. ISSN 2518-4431.
- Bolivian National Science and Technology 1st prize: *"Myoelectric grasper for prosthetic hand"*
- 1 Undergrad engineering degree project
- 2 Masters degree projects

What have we done so far?



ed

of joint

To do

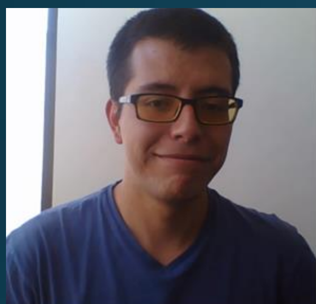
- Redesign joint/actuation
- Characterize new joint
- Integrate joint in hand
- Usability test!

Acknowledgement

The "*Variable stiffness prosthetic grasper project*"

is being funded by the Robotics and Automation Society (RAS) Special Interests Group on Humanitarian Technology (SIGHT) from The Institute of Electrical and Electronic Engineers (IEEE).

Our team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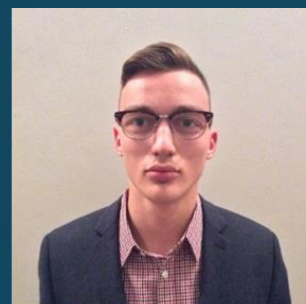
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