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Design and development of two medical devices to assist the rehabilitation of the upper limb mobility in post-stroke patients

Biomechanical Engineering MSc Internship Report at Callaghan Innovation

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1 PREFACE

As part of my second year master studies I completed a four month internship at the company Callaghan Innovation. This company is settled in Christchurch, New Zealand. The 16-week period that I worked there started the 29^{th} of September 2016 and finished the 16^{th} of December of the same year. The working hours were divided between 9 am and 5 pm from Monday to Friday. I worked in the group of Assistive Technologies under the supervision of Dr. Marcus King. In this internship I participated in two different projects related with the design, development and validation of two medical devices to assist the rehabilitation of the upper-limb mobility on post-stroke patients. In the validation part, I was lucky to work with a real stroke patient who used these devices and gave us direct feedback on them.

During these four months I was able to learn how to design a medical product since its initial pre-concept phase until its final market production (one of the devices is thought to be produced next year). I worked on CAD design programs (SolidWorks 2016), software development (Arduino IDE, C^{++} and Windows Visual Studio, the last one as a software development platform) and mechanical/electrical system development (Arduino microprocessing and electrical components). To sum up, the developed devices are a kind of embedded systems that combine all the mentioned features under the control of a microprocessor, which make them actuate in different ways to generate their final function. I also learned how to work with a modern 3D printer and tools soldering or drilling, among others.

Finally, I would also like to mention that I had the chance to work with two other intern students from the Netherlands, with different engineering backgrounds, as a multidisciplinary team. This gave me the opportunity to work on my communication (verbal and written) and teamwork skills. We all worked together in all steps of the projects.

This project would have never been possible without the help and guidance of my supervisor and head of the group where I was working, **Dr. Marcus King**. I will never be able to thank him how much he helped us, not only in problems/questions related with the work we were doing in the company, but also for his advices and comments about New Zealand and how to live this country. I truly felt how he loves it and he made me love it too.

The second most important person was **Tom Glenn** (stroke patient). He showed me how to overcome an stroke (actually he suffered five strokes during two weeks) with the best way possible, being happy. I will always remember the weekly sessions that we did with him (the most intense 30-60 min of the week) and his subjective opinions on what we were working on. He was grateful with us for making that devices and I am grateful with him for being the key point around which all the improvements and designs of the products where thought and applied. I would also like to thank all the team in Callaghan that helped me along these four months. Specially to **Zeus Engineer** and **Ivo Gorny** (Electrical Engineers) for their support on the electrical components part of this project, and **Andree Blair** (group administrative person, and the "mother" of all of us) for her constant interest and help.

2 SUMMARY

This internship is divided into two different projects, a hand exerciser and a toy-like assistive device one. These projects are thought to assist the rehabilitation of patients that lost, partially or completely, their upper limb mobility.

To work on these projects a team of three intern students was made by the company. We all worked together since the beginning until the end of this internship. The idea generation and concept development for each project was done by brainstorming and team session meetings. We followed a traditional design assignment structure.

In the case of the first project, two final ideas were proposed to generate the desired rehabilitation. These devices are assembled on a robotic arm-skate already developed by the company before the beginning of this internship. They both promote the hand grasp/release and the arm pronation/supination movements. These prototypes are printed in poli-lactic acid (PLA) due to its reduced price and good material properties. They were designed in SolidWorks 2016 CAD program. A microprocessor based on Arduino UNO was used to control the system and its electrical components (such as motors and resistors). These motors actively drive the device to generate such movements on the patient.

In the case of the second project, a final Toy device was developed. This final product is thought to assist hand detailed and arm bulk movements on the patient. It has 10 special features that resemble daily actions that these patients may require to recover after suffering from a stroke. Actions such as opening a door knob or sliding a zipper are introduced in this device. The same material, production process and microprocessor used for the first project was used in this one. In that case, it is not an active but a passive device that waits for the patient to actuate on it. It doesn't generate any active movement on any part of the patient's body.

After the products were developed, several validation processes were followed. Every week a stroke patient came to the company to undergo his rehabilitation and test these devices. His feedback was used during the entire process to improve the performance of the devices. After that, a group of medical specialists came to the company to validate the ideas and products once they were finished and completely functional. Some extra recommendations and ideas were extracted from that validation sessions. These can be applied for further improvement and analysis on the prototypes.

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3 TABLE OF SYMBOLS AND DEFINITIONS

Some symbols used along this report are summarized here. Nevertheless, in these projects, not a lof of abbreviations were used.

Name	Symbol
Chest button	CB
Polylactic acid	PLA
Armskate	AS
Pronation/Supination	P/S
Grasp/Release	G/R
Bill of Materials	BOM

4 INTRODUCTION

Nowadays, one of the most important problems of our healthcare systems, and at the same time its success, is the increment of the life expectancy. The needs of the population in healthcare systems have changed in the last decades. On the one hand, the fast advances in medicine are helping to generate longer and healthier lifes. But, on the other hand, this ageing of the population is generating a big load of patients and resources in healthcare systems, sometimes very difficult to manage. The older the population is, the higher the demand for medicines and high-tech health services are. Heart diseases and storke are now the most common mortality problems of the modern world, both related with elderly or older population.[**?**]

In developed countries, stroke is one of the major causes of mortality. Approximatelly, close to 30% of the patients that suffer from stroke die bacause of that. What is more, about 30% of the patients that survive, remain permanently disabled. Nevertheless, for the rest of survivors, the side effects of the stroke change their lifes for ever. Reduced mobility and partial paralisis are two of the most common side effects on these patients. It is also relevant to point that, due to the increase of the life expectacy, as mentioned before, the number of stroke patients is also increased, with a higher incidence in male. For this reason, most of the healthcare investment is associated with stroke patients, their rehabilitation and their after-stroke control [**?**]. With special focus in rehabilitation, attempts to introduce robotic-assisted devices have shown good results in both, patient's recovery and treatment efficiency. [**?**]

A person face an stroke when the blood supply that travels to the brain is interrupted or blocked, partially or completely. In this situation, the neurons stop receiving the required quantity of oxygen and nutrients to live and they start to die. Normally this necrosis is produced by a blocked artery (most common one) or by a leaking of a blood vessel in the brain. The main risk factors for a stroke to be produced are the ones associated to old population and unhealthy habits. Overweight, physical inactivity or alcohol consumption are part of the second group. High blood pressure, high cholesterol level, diabetes or stroke-family history, for example, are part of the first group. These ones are more related with medical risk factors rather than lifestyle habits. [**?**]

For this reason, one of the proposed solutions to reduce the healthcare expenses, and at the same time make it more efficient and patient-orientated, is to generate home-based healthcare (or robot/device-assisted rehabilitation) and telemedicine. Focusing on the first one, it is shown that home-based rehabilitation improves the efficiency and outcome of the process. It reduces the in-hospital visit times and makes the entire process more friendly and comfortable for the patient, who actively participate in her/his own rehabilitation. In addition, patients learn how to work independently, after a certain trainning, to avoid future problems related to their disease and physical activity. This idea can be applied to both, chronic and post-stroke patients who lost or got reduced mobility in their musculoskeletal system. [**?**] [**?**]

This is the idea with which the group of Assistive Technologies of Callaghan Innovation is working nowadays. Developing products and devices that can help to make the post-stroke rehabilitation of these patients more home-based and less hospital-dependent. Therefore patients will actively participate and enjoy their rehabilitation process.

For this internship I developed, together with two intern students, two different devices with this purpose. They are found in two specific branches (or researching areas)of the Assistive Technologies group where we were working on. These branches are described as follows:

- Serious Games: Toy-like medical devices for rehabilitation
- Rehab Devices: Robotic devices to assist mobility recovery

One of the devices that we developed is classified in the first researching branch. This device was thought to assist the rehabilitation of post-stroke patients by user-friendly games and daily activities. Specifically, it was thought to be used for post-stroke patients in advanced stages of rehabilitation (the ones that have recovered part of their upper limb mobility) to improve their daily life activities. We developed a device that assists the recovery of the movements required to make, for example, actions such as opening a door, driving, opening a bottle or dial a telephone number.

The second device that we built during this intership is classified in the second branch of the group. It consisted in a robotic-based upper limb mobility recovery device for post-stroke patients. In that case, we developed two final concepts/ideas for this purpose. Further analysis and improvement should be done to properly validate these ideas. Nevertheless, we built up two devices that promoted the hand grasping and arm pronation/supination recovery. Both designs were thought to work in similar ways. They differ in their design, shape, hand grasping and control programme.

Finally we were also working on a third device. In that case, it would be part of the second branch. It is a robotic arm-skate that was developed by Callaghan just before we started our internship projects. This device generates movements that activate the recovery of the entire

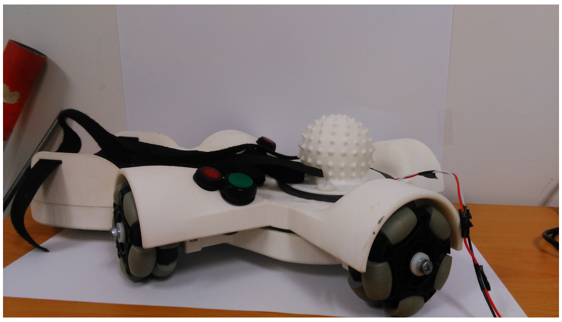

Figure 4.1: Robotic arm-skate developed by a previous team at CI. It is possible to differentiate the ball vibrating handle, four wheels and a support for the arm.

upper limb, from the shoulder until the hand. We only interfered in the design of the ball-like spiky hand grasping handle. This device is a final product and, as it was mainly developed by another team before I started this internship, I won't explain in detail how it works. It consists on a supporting surface for the arm of the patient, a ball vibrating handle for the hand and four wheels that rotate perpendicularly to generate circular movements of the arm and shoulder (see figure **??**). My work with it consisted in the improvement of its use on post-stroke patients, generating a repeatable active procedure, and helping in developing the spiky hand-grasp part.

4.1 Callaghan Innovation

Callaghan Innovation is a government agency created to help improving the impact of engineering companies looking to find market success though research and development. This company works with business of all sizes for almost any type of technology background (from food to medical devices businesses). The main goals of this company are: [**?**]

1. **Accelerate** a product and service development.
2. **Gain** market advantage through leading-edge ideas and products.
3. **Increase** the return on investment in research and development (R & D).

Callaghan Innovation is one of the most important technological companies in New Zealand. It gives services based on a five-star tree action:

- **Technology and Product development**: To improve products or develop new ones.
- **R & D Grants**: To add scale to the R& D investment for greater impact.
- **Access to Experts**: To help making the right connection to solve technology and business problems.
- **Innovation Skills**: To make other business innovate successfully by organized trainings, programmes and workshops.
- **Business Collaborations**: To promote knowledge sharing around technology and innovation.

4.1.1 The group

The group that I joined during this internship is the Assistive Technologies one. This branch of Callaghan Innovation helps business to create solutions for rehabilitation. It is part of the section of Information Communication Technologies (ICT), which combines the data science/analytic and the medical device design and implementation. Together with computational mechanics, simulation and product development/testing they develop medical devices that are ready to make a great impact on the market.

The goal os this group is to create new tehcnological opportunities from innovation in the healthcare industry working with business and academia, both locally and internationally. This group shares a strong relationship with clinicians and patients, who are the final users of their ideas and products. It is also part of the Consortium for Medical Devices (MedTech CoRE) of New Zealand, which provides them the chance to work with professionals of the same branch from all over the country. Nowadays, the group has specialized in four main areas of research: [**?**]

- **Virtual Reality**: Rehabilitation Via Immerse Virtual Environments to help spinal cord injury patients to adjust their life in a wheelchair.
- **Serious Games**: Assitive games for Autism, Paediatrics or Stroke patients with the aim to generate an entertaining environment to improve their rehabilitation.
- **Rehabilitation Devices**: Physical devices to enhance mobility (the ones developed in this internship), hearing, vision, communication and health monitoring.
- **Mobile Apps**: Growing section of technology to be used in direct finger-touch communication. Could be applied to any type of medical condition.

4.1.2 The team

During this internship I have been working with two more bachelor students coming from the Netherlands, from the HZ University of Applied Sciences, as a team. They both have an engineering background with emphasis in medical devices. Nevertheless, one was more specialized in electrical circuits (Bart) and the other one in product design (James).

In order to develop a medical device, we collaborated each other with our own knowledge. Combining biomechanical engineering, electrical engineering and product design was a good start to design a successful medical product.

We divided all the tasks we did during the project. We worked on almost every step of the design process together. In figure **??** in the next page it can be seen the division of tasks that we made at the beginning of our internships. We divided it also in both of the projects that we had to work on. The final task, the one named *game* in this figure, is an extra step. We thought to develop a game for the *Toy* if we had enough time to do so, as it was not part of the main goals or objectives proposed by Marcus King at the beginning of this internship.

4.2 New zealand culture

My experience in New Zealand has helped me to see this world from a completely different point of view. We are not alone. Let me explain what I mean with that. This planet is full of cultures and people, all with different traditions and habits. Nevertheless, at the end, it is possible to realize how similar all of us are. In New Zealand I could experience that. This country is full of people from all over the world. They do not differentiate between races or colours, between regions or backgrounds. "New Zealanders" are one of the most open-minded cultures that I have ever lived in. They are always willing to help each other and the people that come from other countries with fewer resources.

The Maori culture is absolutely present everywhere in New Zealand. Only 18% of its population is Maori, but their traditions and language can be found all around the country. They protect and promote their heritage, which is more internationally seen in behaviour around a simple team sport as it is Rugby. In New Zealand rugby is the most important sport of all. Nevertheless, for them it is more than only this. It is like a religion, a way of life. Children learn how to share with everybody and show respect for the others with it. The Haka, their tribal treasure and national identity, is close to be the national hymn and they perform it in every important event (for instance, at the retirement of a college professor).

Finally, I would like to remark their relation with nature and their environment. This is also part of their culture. This country is a very low density inhabited one. Their mountains, glaciers, rainforests, beaches, wildlife reserves, fiords, tracks and bays are full of biodiversity. They know it and they protect it. Sea lions, seals, penguins, dolphins and whales come to their coasts to mate. Some of the most endangered species of birds (some of which I was lucky to see in the nature) can be found in their islands. A very little wingless one of them, called Kiwi, defines them as the "Kiwis". I think that this environment makes them one of the most environmentally friendly societies that we can find.

As everything was not only working during this internship, I would also like to share in this report the places that I have visited during my leisure time these 16 weeks (*see* **??**).

4.3 Report structure

In this report I will explain the design process that I followed during my internship. As I was working in a team, I will tend to use the plural to refer to what "*we*" did and not to what "*I*" did. In the cases where I worked alone in one specific point I will use the singular person.

First of all I will define the problem that we had to solve for this internship and the motiva-

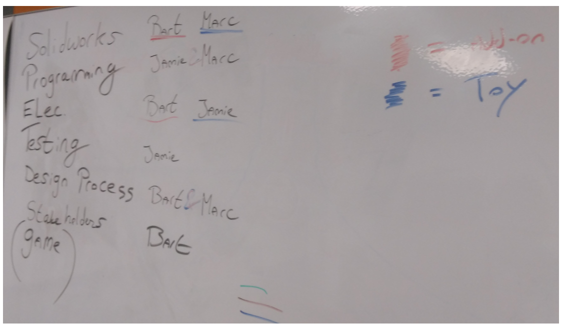

Figure 4.2: Expected task division for the internship.

tion to do it. Then I will continue describing the pre-concept generation and idea creation process that we made. In that step, we generated possible solutions for the two projects that we were asked to develop. From now on I will refer to them as "*Add-on*" and "*Toy*" projects. After that, the final concept/s will be selected and, during the detailed engineering step, they will be further developed and explained.

Finally, the validation of that final concepts/products will be explained, the conclusions will be extracted and some extra recommendations for future projects will be suggested.

5 PROBLEM DEFINITION

As mentioned before, stroke is more probable to affect old populations, over 55 year old, with a greater incidence in male. They are part of the risk population and, for this reason, they have to take regular revisions and keep control of risk factors related to their lifestyle. For example, patients of that age with high blood pressure or diabetes, must be under constant control and, probably, under medication.

One of the principal side effects of an stroke is the lose of locomotion of some parts of the body. Normally both, walking and hand/arm grasping are specially affected in different severity levels. This makes every patient an individual and special case of study. Not all of them answer in the same way to rehabilitation (done by physiotherapy or by robotic assistance).

Focusing on the upper limb recovery, there is very little available in the medical device industry that can assist this rehabilitation. A lot of research is focused on big exoskeletons and robotic devices that can interact with the patient and then, through a feedback control system, generate some actuation on him/her. Nowadays these systems work well and, what is more, they are shown to have very positive results in stroke patients. Nevertheless, they are unaffordable technologies for most of the healthcare systems and hospitals of many countries. In addition, they normally need an expert professional to use the robot and train the patient on it. It is impossible to bring it home for a daily basis rehabilitation. This makes the use of this devices boring and extremely expensive for patients conducting post-stroke limb rehabilitation.

For this reason, and regarding the fact that the patient is the central part in the development of any medical device, small, easy-to-use, portable and cheap devices are required in this field. This was the main objective of this internship and, considering all this requirements, two different devices and concepts were developed for stroke rehabilitation. One of them will be applied to recover the hand grasping and pronation/supination of the arm, while the other one will be used in detail and daily life activities recovery.

6 List of requirements

The final part of the analysis was addressed to generate the specific list of requirements for both projects. With this list, the design goals can be determined and the first pre-concepts can be generated. It must be said that the list of requirements was developed with requirements from the company and costumer, the own ideas of the design engineers and some feedback of the patient at the end of the process.

6.1 Hand Add-on

In the list or requirements of that device issues like required movements and simplicity of the device were considered. It must be said that features like *flexion/extension* and *radial deviation/ulnar deviation* movements were firstly analysed and finally discarded from the list because they are not so essential in the distal upper limb mobility recovery and the difficulty to design a unique device with all these motion characteristics. The final list of requirements is as follows:

1. Simple design and actuation
2. Low cost/Affordable
3. Movement requirements (see figure **??**)
   a) Pronation/Supination
   b) Grasp/Release
4. Small in size
5. Modular on/off system on the arm-skate
6. Ergonomic adaptation to the patient's hand
7. Light and strong material
8. Repeatable production process

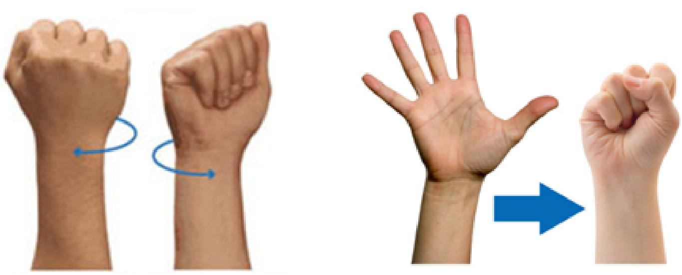

Figure 6.1: Pronation/Supination movement (*left*) and Release/Grasp movement (*right*)

6.2 Toy

In the Toy the list of requirements is a bit different. Here, it is not necessary to actively stimulate the patient, but to make him do "all-day" activities and actions with the device. This stimulation can be visual or auditory. The actions to be done by the patient can mix big and bulk movements with very detailed ones. At the beginning of this internship, a list of possible actions that the patient could do with the device was made. During several group meeting sessions, we selected the more relevant ones for the final list. In that case we did it with feedback of our supervisor, Marcus King, and the costumer to whom the device was being designed. This final list, together with other design requirements of the device, is shown here:

1. Actions to be generated:
    a) Blow a turbine
    b) Press a button with the chest (Chest Button)
    c) Turn a door knob and its key
    d) Slide a zipper
    e) Open/close a jar lid
    f) Press buttons of different sizes
    g) Tilt the device
    h) Shake movements
    i) Squeeze with the hands
2. Introduce some kind of stimulation to make the patient use that actions
3. Drive it automatically
4. Make a game out of the actions to combine rehabilitation and playing
5. Embed everything in a portable, easy-to-use, affordable and user-friendly design
6. Dimensioning of the device and looking for the patient/s

The actions that are thought to be applied in the device can be classified as bulk or precise actions. The bulk actions would generate long and strong upper-limb movements (in this group we find the Chest Button, the Blowing of the turbine, the tilting of the device and the shaking). On the other hand, all the other actions, would correspond to more precise hand-based movements. The combination of both in this device would dramatically improve the rehabilitation of these patients with lose of upper-limb mobility.

The introduction of a game in a rehabilitation device was shown, by the previous experience of our supervisor and the group, to have a very positive impact on patient's rehabilitation. If patients enjoy using the device, they will use it more and for longer periods. The patients will not even notice that they are improve their rehabilitation at the same time that they enjoy playing with a game or toy.

7 Conceptual engineering

In this section, the first part of the synthesis is presented. The pre-concept generation for each device, its analysis, the list of requirements and the final concept selection will be explained here. Also the procedure followed to generate ideas and concepts is summarized in this part.

7.1 Pre-concept generation

7.1.1 Hand Add-On

In this project a device meant to help the recovery of the upper limb mobility must be designed. As explained before, there is a robotic arm-skate available in the company that assists upper limb active rehabilitation. The idea of this project is to develop a kind of *module* to be placed on the hand-grasping area of that device. According to the list of requirements, it should be replaceable and it must has a simple type of driving force to move the patient's arm automatically. For this reason, the name of *Hand Add-On* was decided for it. Ergonomics design and sizing of the device must be considered as a relevant goal in order to both, make it fit on the arm-skate and adapt it to the patient's body (in that case her/his hand and/or arm). Finally, considerations regarding the production process and it's affordability will be considered. Nevertheless, as suggested by the company and due to the previous experience of the group, 3D printing will be the production process to which the design and the material should adapt to. It also meets the requirements of a repeatable process and introduces the use of a cheap and light material (PLA), which can be modified or shaped to be stronger in some specific parts.

In order to generate ideas for the first pre-concepts, several brainstorming sessions were made between the three components of the team. From these sessions a series of ideas was generated to meet the pre-defined requirements. With them, some pre-concepts were built. The ideas are shown in the following tables **??** and **??**, where the requirements are summarized in *Design of parts* and *Mechanisms & Actuation*:

Table 7.1: Design of parts. Idea generation summary

Part	Idea	Description
Grasp/ Release	1. Ball	Ball element with the size of the hand
	2. Spiky cone	Spike on a cone to help placing the hand on it
	3. Shaped cylinder	Cylinder with indentations for the hand fingers
	4. Handle-like	Two handles based on a hand grip exercise device
Pronation/ Supination	5. L-like shape guide	L-shaped base to rotate around an axis and generate this movement
	6. Single axis base	One axis placed under the grasping element
Assembly on base	7. Flat base on AS	Platform to adapt shape of Add-On on AS
	8. Column base on AS	Column to hold the Add-On on AS

The movements and sizing requirements are summarized in the *Design* ideas of this table. The design requirements (table **??**) are summarized in a division of *Grasp/release*, *Pronation/supination* and *Assembly on base*. The last one refers to the assembly of the add-on device on the arm-skate. The Add-on must fit on the arm-skate in a modular way. So it can be replaced or changed by other elements. The ideas thought to do this performance are number 7 and 8, which refer to a flat or a column-like structure that connects the base of the arm-skate with the hand exerciser.

Table 7.2: Hand opening Mechanism & Actuation. Idea generation summary

Part	Idea	Description
Hand Opening	9. Guide around the motor axis	Direct connection of the motor and the opening axis
	10. Double axis threaded guide	Opening and closing with a double threaded tube (up/down)
	11. Mechanic "cam" opening system	Mechanically opening of the hand with a motor driven "cam"
	12. Inflating (balloon) system	Rubber air balloon to open/close the hand
Actuation	13. Stepper motor	Step precision motor. High speed but low torque. Used in 3D printers
	14. Worm gear motor	Perpendicular driving axes, which improves space use. Good torque
	15. Servo motor	PWM position control. Clockwise and counterclockwise programmable move

In the case of the *Mechanism and Actuation* ideas, these are divided depending on "how to open the hand" and "what type of force or actuation" we can use to do it. In the first case three mechanical ideas are presented. Idea number 10 seems to be a bit complex but it could have a good potential to bidirectionally open the hand. It is thought to be used as a double guide where a hand-case can be placed around it and, depending on where the threaded tube rotates, it will open or close the hand. In the case of idea 11, it was extracted from a suggestion of Marcus. With a mechanical ellipse (called cam), a couple of tubes or handles for hand grasping could be resting would open or close because of the differences in the long and short radius of that cam.

From the ideas summarized in the previous two tables, several pre-concepts were generated. Then, they were discussed and analysed with the help and supervision of Marcus King. In the next section (*Concept Selection*), the final pre-concepts will be selected and they will be further analysed in the detailed engineering section. The next list, table **??**, shows the pre-concepts generated for the *Hand Add-On* device. The pros and cons are here analysed and defined with a + or - sign. This will be used later in the concept selection process.

Table 7.3: Pre-concept summary

Pre-concept	**Short Description**	**Pros and Cons**
1. Guided P/S and ball-like grasp	Ball shaped handle with flat base Two separated joints for move. Ball single axis module inside P/S axis. Spherical air-inflating for G/R	+simple +compact -bulk -size -actuation space -ergonomics -control of move -G/R design
2. Ball/Cone-like grasp with flat base	Ball shaped handle with flat base Two separated joints for move. Circular grasp with spiky peak for easy grasp. Guide for open/close the G/R	+simple +compact +bulk -size -actuation space -ergonomics -control of move -G/R design
3. L-like base and cone grasp	Similar handle to 1/2 + L-shape for P/S Two separated joints for move. Different loading distribution Guide for open/close the G/R	+control move +actuation space +modular shape +ergonomics +rotation -complex -strength -G/R design
4. Three-door grasp and L-like base	Similar handle to 1/2 + L-shape for P/S Two separated joints for move. Adaptable sizes. Opening cone. Double threaded axis for open/close G/R	+size +modular +actuation space +control +ergonomics -strength -complex +G/R design
5. Double handed with rotating cam	Parallel single axis movements Two levers for hand grasp. Rotating cam for opening/closing and P/S Column-like structure for assembly	+control move +actuation space +modular shape +ergonomics +rotation +strength -complex +G/R design

7.1.2 Toy

This project has a completely different approach. In that case, a device to "make the patient do" some specific actions should be designed. Here some different aspects should be considered, compared with the previous device. The combination of good design, for both the entire device and every specific action, with electronic control, software control and patient stimulus is the most difficult part. Some ideas were generated following these last 3 specific parts. The summary of that is shown in table **??**. The designs and external shapes of this device are inspired in a product called "Bop-It". This toy, available in the market since some years ago, performs five different actions that the user (in that case children) had to reproduce as fast as possible. This was the initial point of the idea generation and function design. The software development was based on a game that could interact with the patient as well as the one from "Bop-It" does.

Table 7.4: Electronics, software and stimulus. Idea generation summary

Part	Idea	Description
Electronic control	1. Arduino UNO	Simple and powerful microprocessor. Combination of Software+Electronics
	2. Arduino MEGA	Same as 1. but with more input/output ports
	3. Seeeduino	Same as 2. but from another provider
Software control	4. Game-like structure	Concatenated actions
	5. Repetitive loop	All actions in continuous reproduction
	6. Levels as difficulties	Introduce difficulties for action performance
	7. Time variable	Specific time to do an action
Patient stimulus	8. Auditive	Voice or sound tells what action must be done
	9. Visual	LED or light power to tell the action to do

These ideas are then mixed to generate specific concepts with the *Design* of the possible devices. The next table **??** shows the 6 pre-concepts that were thought for this purpose.

Table 7.5: Pre-concept summary

Pre-concept	Description
1. Gun-like shape	One side with handle and one side with a knob. Features on front/back/side parts
2. Triangular shape	One side with a door knob like handle and a regular one in the other. Features at front/back side
3. Spherical shape	Sphere with features all around it and handles on two perpendicular sides
4. 3D cone shape	Hollow or empty cone with features on it's faces and handles on a specific side
5. Steering wheel	Handles like a steering wheel and features on back and front side. Increased surface
6. Modular object	Steering wheel with a module in the centre for the features

Some sketches were made for this pre-concepts to have a clear overview of their look. This hand-drawings were made in one of the meeting rooms of the company during a team meeting. This is shown in figures **??**, **??** and **??** on next page.

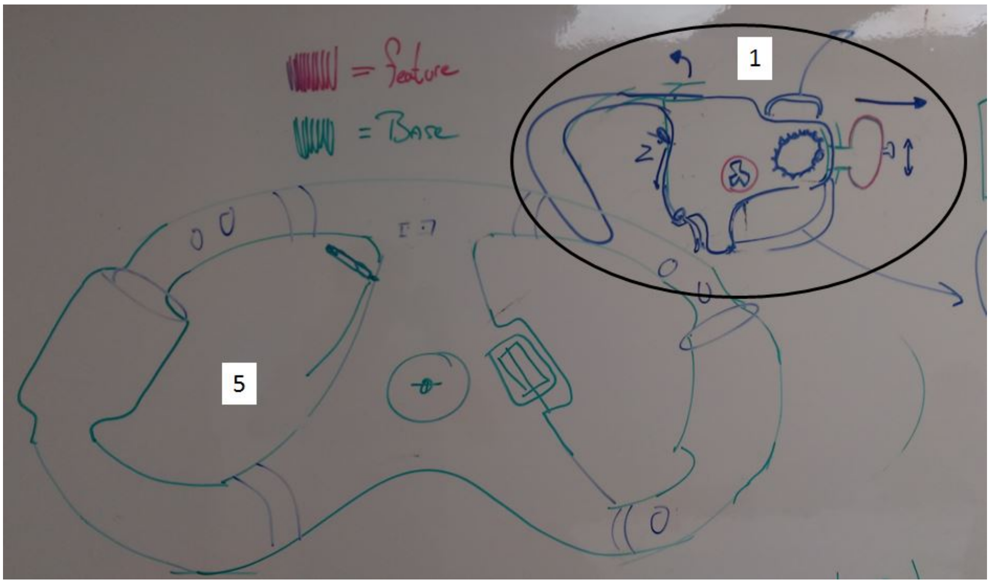

Figure 7.1: Pre-concept 1 and 5 of the design of the *Toy*.

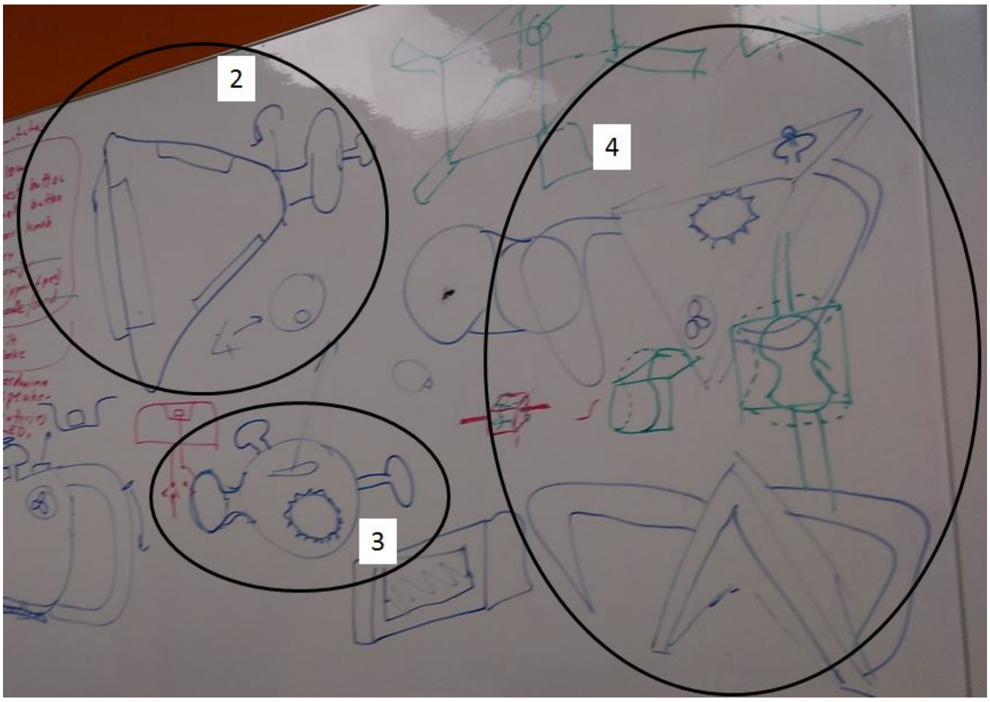

Figure 7.2: Pre-concept 2-4 of the design of the *Toy*.

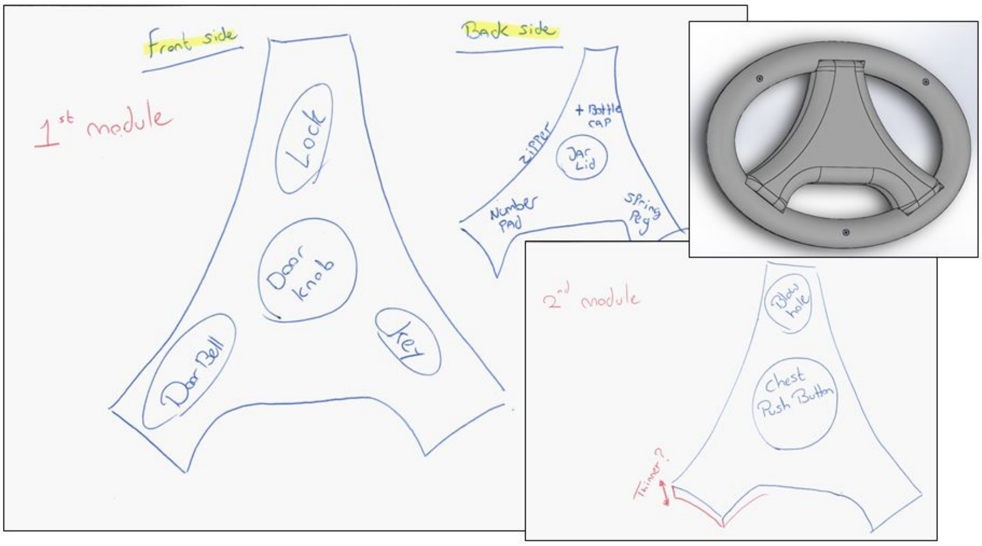

Figure 7.3: Pre-concept 6 of the design of the *Toy*.

All these ideas and pre-concepts consider all the *Actions* that were defined in the list of requirements to be placed on the device. Depending on the shape or size, some features [1]

[1] Now on the word *features* will be used to refer to the daily *actions* that the device must include.

would not fit. The designs or pre-concepts thought to be too small or too complex to fit that actions will be discarded in the Concept selection part.

In the case of the design of each individual features, we didn't develop any type of list of ideas. One person was in charge of designing them. We only decided to follow ergonomics, real design inspiration and hand size standards from DINED database developed by the Technical University of Delft [?] to be in these features or parts. Then, these designs were discussed and improved in general meetings. I was the one in charged of designing each feature. I followed the standards of real life objects. For instance, the door knob was designed as a real door knob. The same for the zipper, the jar lid and the blow features. As the activities that the patient/user must do with the device should be as close as possible to the real one, these parts are designed in the shape of the objects that we can find in our daily life.

In order to develop a final concept, one design will be chosen. Then, the final concept will be built from the best idea from the list of ideas made in the electronic, software and patient stimulus requirements.

7.2 Concept selection

This step was used to select the final concepts from the pre-concepts developed in the previous section. In the case of the hand add-on, a qualitative process was followed. Direct feedback from Marcus King and the costumers were used to approach the final pre-concept/s. Their suggestions were used to select the final concepts.

In the case of the Toy, a more quantitative process could be followed to decide on the final design of the device. Having chosen that, the rest of elements were decided depending on the availability of materials in the company and the feedback ideas from the supervisor.

7.2.1 Hand Add-On

Pre-concepts 4 and 5 were selected to be the final concepts in the Hand Add-On application. In that case, these pre-concepts have a higher number of pros than cons. This means that, for this application, they were thought to make a better impact in a final design. The main important features used to choose them were: **Size**, **Ergonomics**, **Control of move**, **Armskate attachment** and **Easy-to-make**. These two designs are thought to have a better G/R performance. This movement is one of the most basic requirements for that device. At the end, this feature had a bigger weight in the selection of these two pre-concepts in front of similar ones like number 3. Pre-concept number 3 has a good rate of that features, as shown in the third column of table **??**. Nevertheless, pre-concept number 4 meets the same requirements and, in addition, it also includes a better grasp/release design, according to our supervisor's experience. The design of the pre-concept 5 for the G/R feature is a completely new approach. It's singularity and innovative design made our supervisor suggest that this one should also be further analysed. This is the main reason why 2 pre-concepts were chosen for this project. The figures of the not chosen pre-concepts can be seen in **??**.

As a summary, pre-concept number 4 combines the ideas made in tables **??** and **??**. Specially, it takes idea 1 and 2 to generate the hand G/R movement, idea 5 for the P/S, idea number 8 to assemble the device on the arm-skate base, idea 10 to make the hand opening and ideas 14 and 15 to actuate the system. A worm gear motor will actuate the G/R movement due to the lack of space in the L-shaped base and a servo motor will be used for the P/S.

Pre-concept number 5 also combines these ideas. It takes idea number 4 to generate the G/R movement, idea 6 for the P/S, idea 8 also for the assembly in a column-like base on the arm-skate, idea 11 for the hand opening and idea 15 for the actuation. In this design, the same actuation is used for both movements with the help of another mechanism. The use of two coupled gears is suggested before to analyse this pre-concept in detail.

7.2.2 Toy

The best design, comparing all pre-concepts, was decided depending on it's size, the space for features or actions, the shape and how "beautiful" the design is. "How the device looks" is important because the final aim of this device is to be a toy that the user should like and enjoy to use. We inspired this selection in the successful "Bop-It" toy, whose looking helped it to be an addictive object for children.

In order to select the proper pre-concept design, a more quantitative process was followed. All pre-concept designs were analysed according to four principal features, as mentioned before (or key points, following the definition done in the previous project): **Size**, **Adaptation of features**, **Complexity** and **Looking**. In case of the size, the smaller the device is, the more compact it would be. This would make the device easier to use and more user-friendly. The adaptation of features summaries the embedded combination of the features and the bulk design of the device. Space for the features and the electronics components are included in this point. Regarding the complexity, the simpler the device is, the better it's adaptation of features will be. This means that very complex designs will rate very low in this category. Finally, in the case of the looking. The nicest the design is, the easier it will be for the product to be accepted and used by the patient.

This selection process was performed giving a value for each category in each design. This value is found in a non-consecutive range of numbers. This way, the final selection is easier to differentiate from the rest of designs. These values are 1, 3, 5 or 7, being 1 the minimum and 7 the maximum rating. Finally, an average value is found and the best design is chosen. Table **??** shows this process below.

Table 7.6: Toy design selection

Pre-concept	Size	Adaptation of features	Complexity	Looking	Average
Number 1.	5	5	1	5	4
Number 2.	7	3	3	5	4.5
Number 3.	7	3	3	7	5
Number 4.	7	5	3	3	4.5
Number 5.	**5**	**7**	**5**	**7**	**6**
Number 6.	5	5	5	5	5

The design that better fitted the requirements was number 5. This one was selected for further analysis and development in the detailed engineering section. It rated the highest in adaptation and looking due to its design. We all agreed that this system would have the perfect surface are to match with all the required features. It's shape, which resembles an steering wheel from an F1 car, would make it more appealing for the user. It also had a good complexity rate. Nevertheless, in this section, there were no design that rated on the top value. All of them introduce some aspects that make them a bit or very complex. In the case of the selected one, the main problem was to think on how to determine a proper sizing for the required elements. The available space "inside" it was also a bit more reduced than other pre-concepts such as number 2. For this reason a very detailed inner design was required. As one of the requirements was that this device must be portable, it should be able to fit all the electronic components and the microprocessor board inside it's casing.

The rest of elements on the device were selected by material availability, our own experience and the ideas proposed by the supervisor and the costumers. The **electronic control** will be a Seeduino. This board is cheaper than an original Arduino, and it includes as many ports as an Arduino Mega. In this device, it is important to have as many ports as possible, because there is a large number of features that need to be connected inside the toy. Not only switch features, but also lights (LEDs) could be used, some kind of audio, and extra sensors for one feature. Following this selection, the **patient stimulus** is decided to have a mixture of auditive and visual elements. An audio was thought to be used to tell the patient the feature to do and if the feature was properly done. Then, the **software control** would include a game structure, with several difficulty levels (in a game-like structure) and time variables as an increment of the difficulty of each level.

8 Detailed engineering

In this section the final concepts for both devices, the Add-on and the Toy, will be developed in detail. It's design, 3D printing, assembly, electronics and software will be explained here.

8.1 Hand Add-On

Pre-concept 4: Add-On 1

This device takes a final shape of a grenade. It has 3 cases, where the hand of the patient is placed, whose opening and closing movement recovers the hand grasping/release. Then, due to the L-shape base, the pronation supination movement is generated by rotating it to the adduction and abduction axes of the arm of the patient. The final device is shown in **??**. It is possible to see the grenade casing system (element 1), the L-like base (element 2) and the column system that connects this device to the arm-skate (element 3). Then, the mechanism that opens and closes the casing is shown with elements 4, 5 and 6.

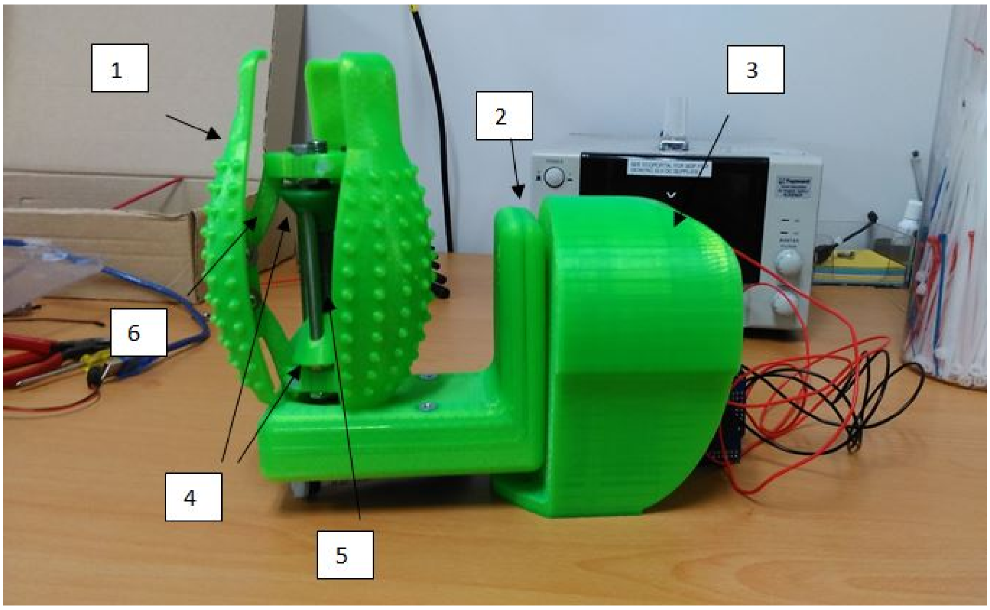

Figure 8.1: Side view of the hand add-on 1 device.

This opening and closing mechanism consists on a double threaded tube which is 50% threaded to the right and 50% threaded to the left (element 5 of previous figure). Two cones are placed in each section of the threaded tube to move up or down, depending on the side that the tube rotates and due to this double counter thread (element 4 of previous figure). The move of these cones opens and closes a group of six bended arms (element 6 of previous figure) that are connected to the 3 cases (2 arms each). These arms make the cases to open and then also the hand of the patient. When the inner tube is rotated in the opposite direction the hands of the patient are closed just by holding on the cases. The mechanism can be seen in more detail in figure ?? below.

Figure 8.2: Opening and closing mechanism of the Add-On 1. Left: Real 3D printed parts for opening (left) and closing (right) configuration. Right: 3D detail of the mechanism and the L-like base with the pronation/supination mechanism shown.

The pronation/supination movement is generated with a system of worm+circular gears. This mechanism is shown in figure ?? right image. This element helps rotate the L base by actuation of a motor on this gear system. A ratio of 1:1 was selected in the gears to keep a better control of the amount of deviation generated in the arm.

The final 2D technical drawings of this design can be found in ??.

The electrical schematic of this device is very simple, as shown in ??. In that case only two 9V DC engines were required to move these parts. The engine that rotates the hand tube is placed inside the L-base, while the one that rotates the entire L-base is placed inside the column. As these engines required a big amount of energy to run, this device can only be used when connected to a voltmeter. No batteries were designed to be placed inside the case.

Finally, the control of the rotation of the engines is done by an Arduino UNO microprocessor. The software designed in that platform generated two rotations of each engine separately. First it opens the hand rotating the worm gear motor. Then, once the hand is closed again, the other motor is rotated to produce the P/S movement. This pronation/supination movement can be better seen in figure ??.

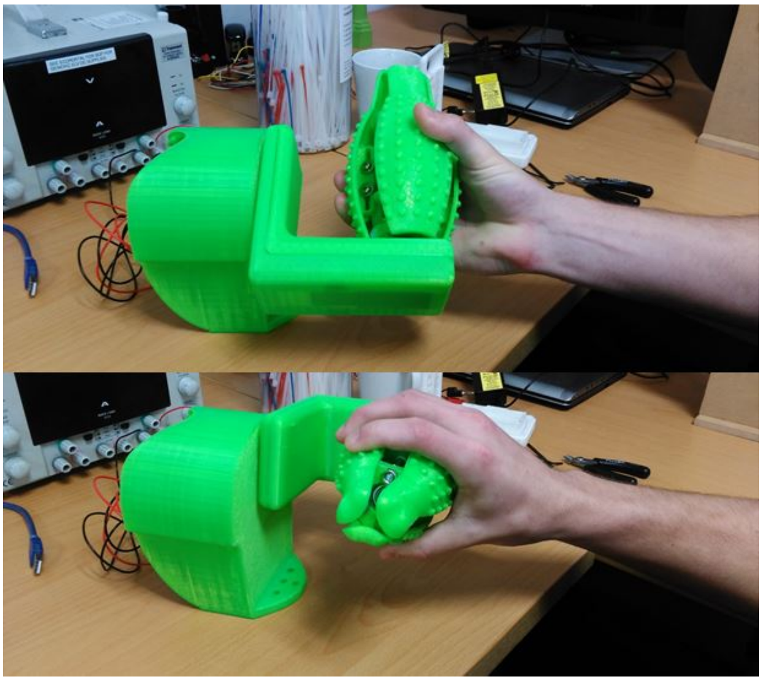

Figure 8.3: Pronation and supination movement generated by the Add-on 1 when a patient is using the device.

The final list of materials and the budget used for this device is shown at **??**.

Pre-concept 5: Add-On 2

This device has a final shape of a double handle system with a column base to connect the device to the arm-skate. The final design is shown in figure **??**. The two handles are ergonomically designed to hold the hands of an adult patient (elements 1 and 2). Then, a small elliptical cam is used to mechanically open and close these handles and produce a hand grasping/release movement (element 6). The pronation/supination movement is then generated from the column base and the semi spherical space created there (element 3). The connection with the handles and the column base helps to translate this movement to the hand of the patient (element 4). Finally, an extra element was introduced in this device. A finger grasping surface was designed on top of the handles (element 5). This surfaces perfectly fit with the finger of an adult patient and can help to recover also the detailed movement of finger grasping/release.

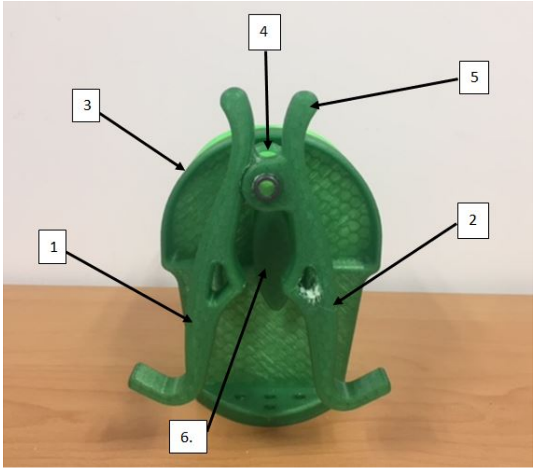

Figure 8.4: Pronation and supination movement generated by the Add-on 1 when a patient is using the device.

The movements of this device are specifically shown in next figure **??**. There it is possible to see how the cam opens and closes the handles when it rotates to one side or the other. Then, the pronation/supination can also be seen when the handles are gradually rotated to the left or right. In that case, a new feature can be added to this design. By programming the movement of the cam and the handles for the G/R and P/S, it is possible to generate a G/R movement when the hand is in pronation or in supination. This is seen in picture 1 and 2 of that figure too. A tension spring was added at the end after feedback from the patient. This spring makes the handles to come back to their closed position after the movement is done.

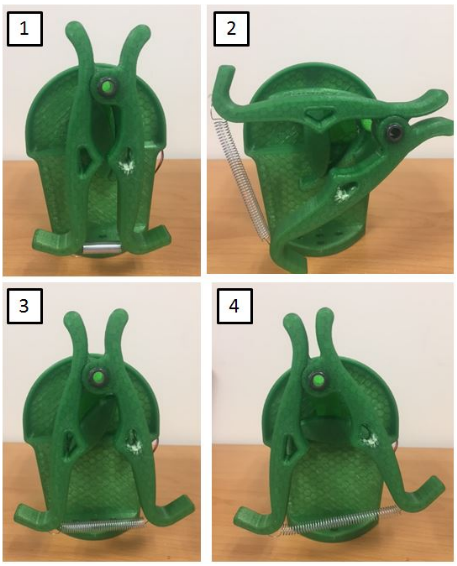

Figure 8.5: Grasp/release and pronation/supination movement generated by the Add-on 2 using the cam. (1) Closed position, (2) P/S, (3) start opening the cam and (4) G/R.

The final technical drawings of this design are shown in **??**. There, the 2D and 3D designs of that device are shown in detail and size.

The electrical scheme of this device is even simpler than the previous one. It can be found at **??**. Only two servo engines are used to drive the two movements of this device. In that case the mechanism is simpler than the previous add-on 1. In that case one servo engine is directly connected to the cam to promote the G/R move. Then, the second servo motor, is places just next to it. With a gear connection to the shaft of the cam, the outer P/S of the handles is driven. Both motors are found inside the column-like base. In that case a 9V battery can be used to run both engines, whose are controlled by a program charged in an Arduino UNO. This program generated several rotations of the cam and then the handles, separately. But is can be modified to generate any type of rotations at any desired order. This device is shown in figure **??** with the hand of the patient.

Figure 8.6: Grasp/release and pronation/supination movement generated by the Add-on 2 using the cam. (1) Closed position, (2) P/S, (3) start opening the cam and (4) G/R.

The final list of materials for this device, and its budget, is found in **??**.

8.2 Toy

This device is divided into three specific parts. The first one, the bulk design of the device, includes a total of ten features, as specified in the list of requirements. At the end, the design was slightly modified to reduce it's weight and make it resemble a bit more to an steering wheel. For this reason, the upper rings of the handles were removed. A electronic schematic that fits inside this case is designed. It's components and structure will be explained here. Finally, the software used to drive this Toy as a rehabilitation game will be detailed.

8.2.1 DESIGN

The first step on this device was the design of it's case and all the features with a CAD software. Then, all of it was 3D printed, as explained before. First of all, the final casing will be shown and then each feature will be explained in detail individually. The device can be seen in figures **??** and **??**.

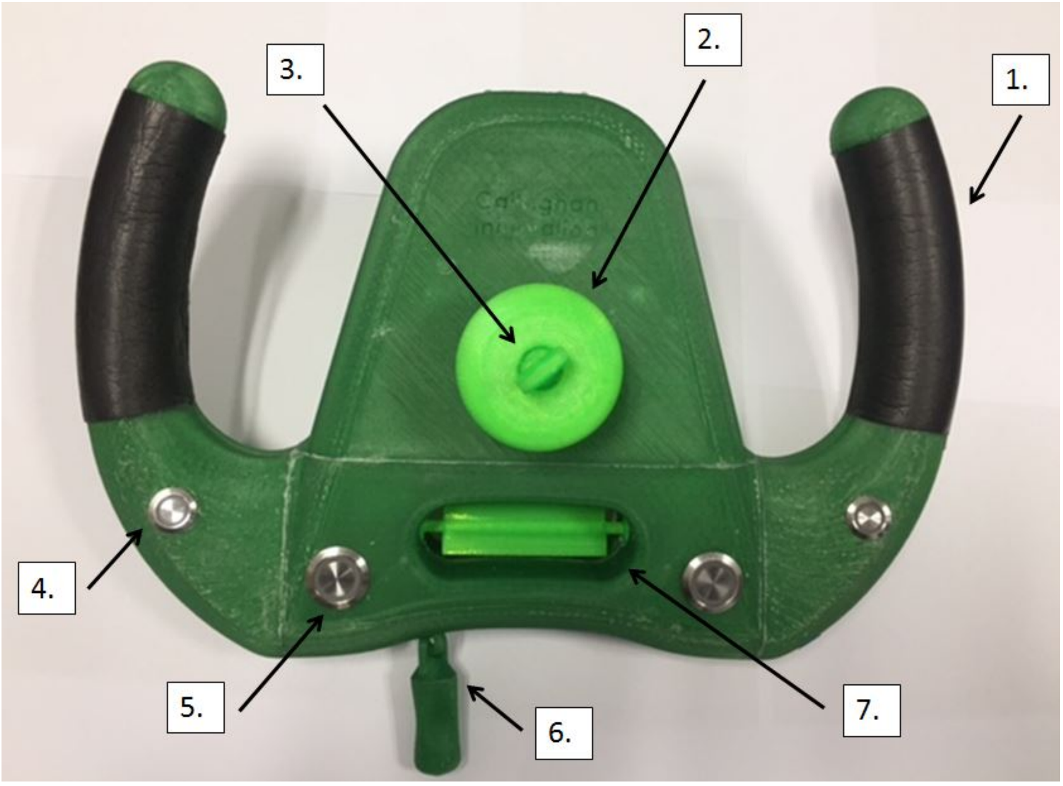

Figure 8.7: Front view of the Toy with each element and features marked with a number.

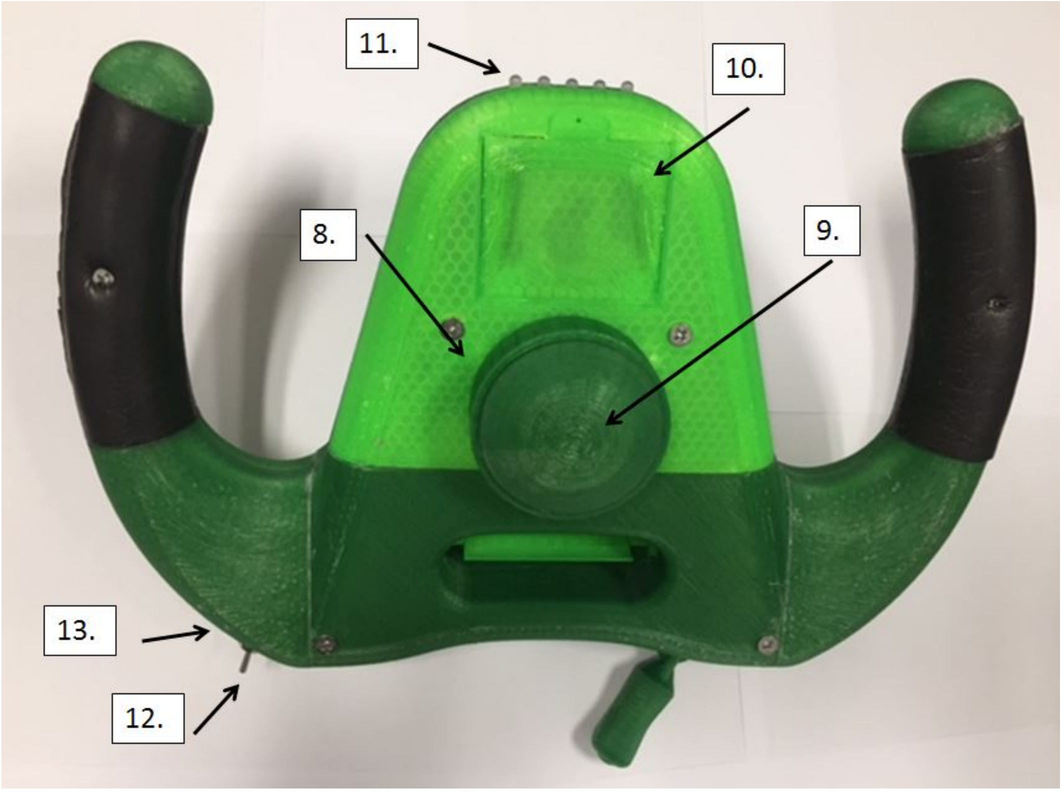

Figure 8.8: Back view of the Toy with each element and features marked with a number.

Chest button and Jar lid

These both features were designed in a single element. The chest button has a circular shape and fits inside the hollow jar lid, which has a surface roughness that resembles the one of a real jar lid (from a marmalade or peanut butter jar). This feature is divided into four 3D printed pieces (two for each function). This way both move independently, like a ring moves around a finger. Using both features in the same structure reduces the required space and improves the looking and use of the device. This element was placed in the back side of the final Toy. The chest button has a diameter of 60 mm (plus some extra tolerances depending on the 3D printer). It has a dome-like shape to make it easier to press by the patient. The outer ring of the jar lid has a diameter of 65 mm. The jar lid and the chest button are shown in figure **??** elements number 8 and 9, respectively. Both features are different actions. For the CB the patient has to put the device close to his chest and press it. This is part of the actions called "bulk" movements. For the jar-lid the patient has to rotate the ring around the CB with his hand.

Door knob and key

Also these two features are designed in a single element. This approach was also part of a requirement for these two features, so both of them work together in real life. The aims of this feature are both, to make the patient do the detailed movements of grabbing, pushing and rotating a key, and to make him grab, pull and rotate a door knob. The key goes through the door knob like a real key does. It is designed in four pieces (two for each action like in the CB and jar-lid) with an extra space inside the door knob which allows them to move independently. Different inner diameters for the holes of the door knob and the key constraints the move of the key to make it fit on the surface of the door knob. This element is placed in the front side of the device, as shown in figure **??**. The door knob and the key are marked as number 2 and 3, respectively. This element is a coupled group of two features. The patient has to first push and turn the key to "un-lock" the door and then pull and rotate the knob to "open" it.

Blow

This feature is designed on a shape of an old windmill. It has three bended wings to help the user rotate the blow easily. This bending and the use of three wings allows the turbine to rotate from air coming from any side. This feature introduces one of the bulk movements of the device. In that case, it makes the patient to move the Toy up with his/her arms to close the turbine to his/her mouth. For this reason it is placed in a bottom part of the device, in a tube that goes through one side to another of the device. This way, the blowing action can be done from any of both sides, as seen in figures **??** and **??** (element number 7). The patient here have to put the device up and blow this feature to make it rotate. With it's rotation a switch is activated and the feature is sensed.

Zipper

The zipper is a feature thought to train the finger grasping and the detailed movement of a jeans zipper. For this reason, this feature is shaped as a pen, with three grasping surfaces for the thumb, the index and the middle finger. This features is placed in the bottom middle part of the Toy. It is divided into a grasp part and a guide part. The grasping part has an spherical back-shape that fits inside the guide and allows it to move right and left freely. It's size was decided following the standards from the DINED database. This feature is shown again in figure **??** element number 6. The patient is asked to slide the zipper right and left, regardless of the side of the device that he/she is looking at, to activate two switches and then sense this activity as done.

Buttons

Some buttons are added to make the patient do precise pressing exercises with his/her fingers. There are four buttons on the device, two small and two big ones. This introduces a difficult and an easy pressing exercise. The number of buttons is strictly constrained by the availability of space on the surface of the Toy. These buttons are placed on the front side of the Toy, making it more appealing and with a compact closed shape, as seen in figure **??** elements number 4 and 5. These buttons have a LED ring incorporated that helps the patient identify them easily (together with the auditive stimulus). The patient has to press a bunch of four buttons, which light up randomly with a random color, to finish this feature properly.

Squeeze

This feature promotes the grasping strength of the patient. Both handles of the Toy are designed with a foam surface. Underneath it, there is a flat pressure sensor with a modifiable threshold to detect when the user is pressing or not the handles. These elements are shown in figure **??**, part number 1. The patient can perform two different tasks with it. He or she will be asked to press one or the other in a complete random way. It is possible that the non-affected hand is as well stimulated. But this way the action is more bi-parallel and it doesn't depend on which side of the device the patient is looking at.

Drive

As a good steering wheel, this device introduces another bulk movement to the rehabilitation of the patient. Two ball-tilt sensors are placed like a mirror in a diagonal position in the middle of inner space of the device. Each of them is activated when the tilt of the wheel is over 45 degrees, approximately, to the right or to the left, respectively. The patient is asked to drive the device and both sensors must be activated, in an unspecific order, to properly do this action. This means that the patient will be asked to drive the wheel to the right and left.

Shake

Finally, another bulk movement is added in the device. A vibration sensor is vertically placed in the middle of the device. This sensor is activated when a certain amount of move (in that case vibration or shaking) is generated. In that case, the sharp exercise required to shake the device will help the patient to rehabilitate the stiffness of the upper limb joints and their stability. The weight of the device and its shape also contributes in that continuous muscle tone recovery in the patient's upper limb.

The patient used and played with these features several times. He gave us feedback on that and, what is more important, he enjoyed from his rehabilitation. How he used some of the features is shown in figure **??**.

The final detailed 3D and 2D drawings of the Toy can be found in **??** for final manufacturing. All parts of the Toy were designed with Solidworks 2016 CAD design program.

8.2.2 Electronic schematic

Every feature is detected with a switch or press button. Then, special features are sensed by the use of some sensors. In the case if the squeeze, force/pressure sensors were used. In the case of the drive and shake, tilt ball sensors were used. Nevertheless, in that case, these sensors work as a digital switch, with only an On and Off position.

Then, the patient stimulus was selected to be both, visual and auditive. For the visual stimulus 5 LEDs were placed on top of the Toy, as seen in figure **??**, element number 11. In the case of the auditive stimulus, a speaker was placed inside the body of the Toy. This speaker was programmed with audio sentences that informs the patient which feature he/she must perform at every moment. This audio files where charged on a SD card that is read with a special board that was attached on the microprocessor. The audio mp3 board used was provided by Sparkfun. We selected this board because it is 100% adaptable with the Seeeduino

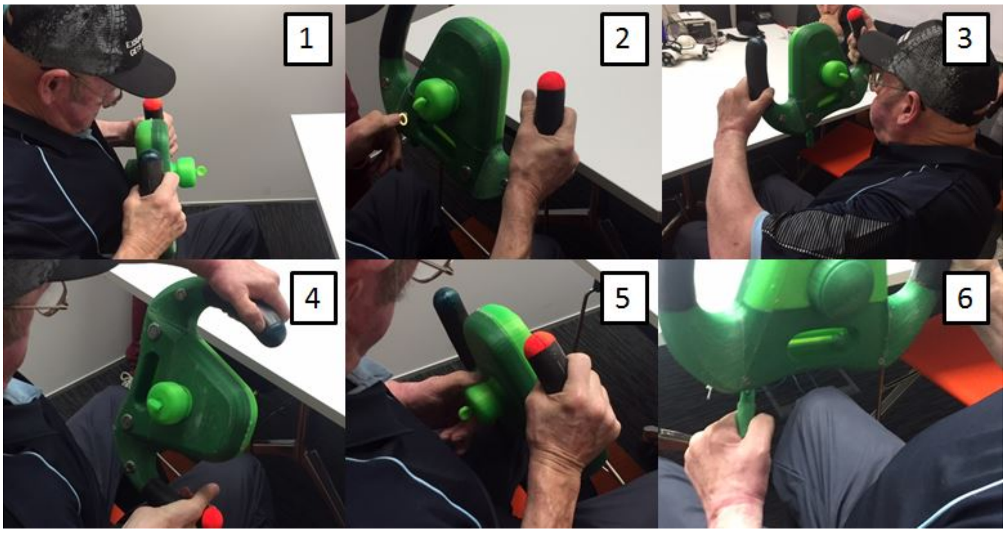

Figure 8.9: Patient using some of the features explained above. (1) chest button, (2) pressing buttons, (3) blow the turbine, (4) drive the device, (5) key and door knob and (6) slide the zipper.

microprocessor and because it has been widely used in this kind of applications.

In order to control the selection of difficulty level, a rotary encoder was used. It gives a four-digit binary result depending on the position of the rotary encoder. This way, by reading its four outputs, the level can be differentiated in the software. This element is placed in the bottom left of the Toy, as see in figure **??** element 13. In order to make this device portable, a battery pack was designed inside the Toy. Four 1.5V batteries are enough to feed the circuit inside. This battery pack is connected to an On/Off switch which interrupts or starts the current of the Toy. Both, the battery pack and the on/off switch are found in figure **??** elements 10 and 12 respectively.

Every switch or sensor that detected each feature of the device is connected with an input pin of the microprocessor (the *Seeeduino* board). This way, it is possible to sense when the feature was done by the user. In the case of the switches, all of them are connected to digital inputs (On/Off signal). In the case of the sensors (force/pressure and the encoder) they are connected to the analogue pins of the board (it reads values between 0 and 1023). Depending on the board resolution, more values can be written by the analogue ports.

8.2.3 Software

The software designed for this device was also developed on an Arduino platform (in that case a Seeeduino micro-controller). This programming language is an object-oriented one. This means that functions and classes are used to define methods and actions in the software. This programme is formed by a main file, which calls and use the functions defined in different classes.

Main code

The main file deploys the general activity of the elements present on the Toy. It initializes all the pins of the microprocessor with the name of the features connected to them. Also the LEDs and the mp3 shield are initialized there. Then, this file generates a loop to make the patient select a difficulty level. An audio is activated for this purpose. The encoder is read here to make the program know which difficulty level should be generated. Depending on this lecture levels from 1 to 8 are selected. In case of entering an "easy" level, the time to make every action is longer, there is not control of the points that the patient can get by doing properly well an action and only some specific actions are introduced. When the difficulty level enters a "medium level, the time is reduced, some pointing is introduced and more actions are done. Finally, if the difficulty level is "hard", the time is even shorter, the pointing system resets if one action is done wrong and all the features of the device can be called.

Once inside one of the difficulty levels, several classes from the program can be called. Each class is differentiated between them depending on the number of inputs and outputs that the function needs to use. Now all of them will be explained.

Class "Action"

This class is used to run the features that only generate one input pin on the micro-controller. This is the case of the key, the door knob, the blow , each squeeze, the CB, the jar-lid and the shake. This class reads the pin where the signal value of each features is connected to know if the feature was done or not. Then, depending on this lecture, it gives a feedback information to the main to generate a new feature.

Class "Button"

In that case this class takes up to four input parameters. This is a very special class that is only used to run the feature of the pressing buttons. It generates a random selection of the button that will light up and the color that it will be used to light it up. Then, when the action is properly done, it jumps to the next button up to 4 times. After 4 times, the class finished and it gives the feedback information to the main code to know if the features were properly done or not.

Class "Turn"

This one only takes two inputs. This is again a very special class used by two features, the zipper and the driving actions. These two features depend on two different switches to know if the feature was well done or not. This class reads this information and tells back the main file if they were well done or not.

Class "PointsLED"

This class doesn't take any input. In that case, this class is used to keep track of the points that the patient gets by doing well an action. As mentioned before, a pointing system is introduced in the toy. This makes it more like a game system. In easy levels this class won't be used. This class saves one extra point every time that a feature is well done. Then, every 5 points, an audio gives feedback to the patient to inform him of how many points he/she got and an LED is lighted up on the up part of the Toy, as shown in figure **??** element 11. The points are counted until 50, when the level finished and the patient is asked to select another level or wait and continue with the same difficulty.

9 VALIDATION

The validation of the devices was done by a direct patient-user contact and with medical experts feedback meetings. Professionals in the field of physiotherapy and rehabilitation in post-stroke patients that collaborate with Callaghan Innovation came twice along that period to evaluate and use the devices.

Once a week, normally on Thursdays, Tom Glenn, a stroke survivor patient, came to the company to do parallel activities to help in his rehabilitation. This was the principal flow of validation that we received during the internship. Nevertheless, we were in daily contact with our principal supervisor, Marcus King, who gave us the advices and feedback that we needed to meet the requirements of the costumer for who these devices were being developed.

Background

Tom was discharged from the healthcare system of New Zealand with no hope for mobility recovery in his upper limb. After some months of that, my supervisor, Dr. Marcus King, contacted him to offer him the possibility to work together in the development of a series of products and devices to help people like him, real survivors. This first contact was made a year and a half before I started this intership. Some devices that the group Assistive Devices of Callaghan Innovation developed are now available in the market, helping stroke patients in their rehabilitation, mainly thanks to the validation and feedback done by Tom.

Direct opinion from users (in that case patients) is crucial in the development of a good medical device. It is thought to be used by patients, and it is them who have the last words about it. A product can perfectly work, can be very easy-to-use according to the engineer experience or it can have thousands of functions to improve the life of people. Nevertheless, if patients don't like it, if they don't find it useful and affordable or if it is harder for them to use it rather than doing any other type of rehabilitation, the product will fail. That is the main idea around which my supervisor and his group work.

Do products for patients, improved by engineers and validated by patients

The sessions with the stroke patient

Once a week the patient Tom Glenn visited the company to do his regular rehabilitation with us. At the beginning only the arm-skate device was being used because the other devices were under development. We used this sessions to get feedback from the patient about what we were planning to introduce in that new devices.

Each session consisted in 30 min of use of the arm-skate device (as it was not develop by us I am not going to further explain it here). After that, the patient was opened to use the other devices that were being developed by the group (so, not only our products) orientated to improve the post-stroke upper limb rehabilitation. Every week some improvements were introduced in them until the final products that we developed. Even though the Add-On devices are still under development and they need further redesign and test, the TOY is ready to be manufactured. Some small changes and redesigns should be necessary to adapt it to the product standards of New Zealand.

Medical feedback

When the devices were starting to become "real", we had some meetings with medical collaborators from Auckland and Wellington. They came to visit our group and the products that we were building not only to share their opinions about them, but also to give us their ideas and show us the work that their were doing related with stroke patients in their own fields. This sessions were a day-long meeting where everyone, not only us as interns but also the principal researchers and engineers, presented the advances made in their products.

The structure of these meetings was like a normal group meeting of any researching group. First the person that has been working on something introduces its research/project/product. Then everybody can ask questions about that. If there is already a product developed, it can be shown and used to the medical experts and to the other members of the meeting. Finally, some feedback and discussion can be done, by anyone (also from the interns) on that presentation.

I am personally very happy about these meetings with experts because everything that we were developed was made for them. For this reason, what they can think or say about that products is crucial to accept it as a valid idea or not.

10 Conclusions

First of all it can be concluded that three functional devices were developed during this internship. Two of them can be used for the same application. Nevertheless, the Add-On 2 is a more compact design which adds an extra movement to the hand rehabilitation (the finger G/R). All the devices are thought to assist the rehabilitation of the upper limb in post-stroke patient who had lost the mobility of this area.

I can also conclude that with this internship, a high level of team work skills were obtained. The fact of working in a team for these projects dramatically trained the communication skills of the three members of the team. The fact of working with people with different background and from different countries, also helped us to be more flexible and opened to hear different opinions and working habits.

The Add-On devices are designed to be placed on the surface of the arm-skate. This way, a complete upper limb rehabilitation can be conducted. These devices were tested with the patient and, despite they can be improved, the initial outcome is very satisfactory. They are not at the final stage of development. Further analysis and maybe reconsideration on design are concluded to be necessary to improve the motor driving forces that generate the desired movements.

A new mechanism was developed in the Add-On 1 device to open and close the hand. This mechanism takes a very small space and it can be placed inside the hand grasping part. It was concluded that it works, despite its complex production process.

In the case of the Toy, a final product was developed. It is thought to be manufactured next year, after some extra considerations. It was concluded that the weight and the activities that this toy generated on the patient are good enough to have a complete rehabilitation process, as said by the patient Tom. This device is designed to be used by patients in mid-advanced stages of rehabilitation. For this reason it is decided that the Add-On devices, together with the arm-skate, would be used for the initial recovery of the upper limb. Then, the Toy can be gradually introduced to promote the rehabilitation of detailed and daily movements. The features designed were all properly done by the patient. They promote the actions for which they were designed. After patient's feedback, it can also be concluded that a funny and attractive game was developed with the software program. The 50 points of maximum features was enough for the patient to be happy with his performance with the Toy. The use of different levels also "motivated" the patient to practise better during the feedback sessions.

Finally, it is possible to conclude that portable and affordable rehabilitation devices were developed. The budget required to build the Add-On products was lower than 120 $ (a bit less than 100 Euro). In the case of the Toy, a device cheaper than 1000 $ was built (around 700 Euro). This helps to manufacture this products and start selling them by rehabilitation centres and specific home-assisted companies, reducing their costs and increasing their rehabilitation impact on their patients.

11 RECOMENDATIONS

A final list of recommendations/improvements is suggested in this section. A deep reflexion on each part of the devices, and the design process, was made to generate this recommendations.

1. Some more feedback with the patient is suggested to be done at the beginning of the process. The use of the ideas and opinions of the final user in the design process should be gradually introduced to improve the final functionality of the devices. After all, it is he/she who will decide on buying or not the rehabilitation product.
2. Further analysis with both Add-On devices is required. The torque forces generated in the Add-On 2 are not strong enough. The motors used do not generate the forces that their specifications say. This is happening probably because they were bought from the platform AliExpress, which is not 100% reliable.
3. The Add-on 1 casing should be better assembled. The three cases are not completely in equilibrium when the case is in opened position. An extra arm or balancing element should be designed to improve this movement.
4. The cable connections of the Toy can be improved. The inner part of the Toy was not shown because of the mess it has inside. Every feature can receive up to 4-5 cables to connect the ground, the signal and the 5V feed from the Arduino board. This makes the assembly more complex.
5. The jar-lid feature can be bigger. At the end of the process we realized that it had almost the same size as the door knob. Normally jar-lids can be way bigger than the one we designed. Using a circle of around 80 mm in diameter would be better.
6. The audio used in the Toy was generated by the computer. It is suggested then to build a better audio by recording in a silent room or finding a better computer-based audio generator.
7. Still related with the audio, the speaker used was just for testing. It was part of a bigger speaker that we adapted for the Toy size. A reduced size and more adapted speaker should be used in this application to improve even more the audio of the Toy.
8. The On/Off switch of the entire Toy should be changed. It is too long to be placed on the bottom part of the device and, at the beginning, the patient was accidentally switching off the device just by putting the Toy on his legs.
9. The sensing of the tilt feature (driving) can be improved by using a real inertia sensor. The ball switch used is a good approximation to show that this feature really works, but in a final product, a better sensor should be added to improve the performance of the Toy.

10. After doctor feedback, it was suggested that the arm "up" movement generated by the blow works should be changed. It is not a clean performance to blow a turbine inside a healthcare environment because of possible spitting of the patient.

11. Regarding the 3D printed elements, it is suggested to use a bigger 3D printer to print big parts such as the Add-On column base and the casing of the Toy. These parts were divided into 3 and 8 parts respectively to be printable in the printer that we had. This recommendation is not very easy to be accomplished, because such a big 3D printer is normally not available for selling and the products have to be outsourced, increasing the final budget of the device.

12 Bibliography

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13 Appendices

Appendix A: New Zealand

In this appendix I would like to share the back side of this internship. I will add here some photos of trips done in the country. I was lucky I could travel all around the south island and part of the north island. I don't have all the photos of the north island trip, so I will only show some of the south island.

(a) Christchurch

(b) Lake Coleridge

(c) Milford Sounds

(d) Mount Cook and Hookers Valley glaciar

Figure 13.1: First group of photos

Figure **??** a shows one picture of the city centre of Christchurch. This city was hit by a big earthquake on 2011 that destroyed part of the city centre. Still now they are rebuilding parts of it. In that photo one of the principalm avenues is shown. Next to it, picture b, shows Lake Coleridge from the top of one of the first peak hikes that we made. Under it, in picture d, it is possible to see one glacier at the end of the lake. It correspond to the biggest glacier of the east side of Mount Cook (tallest of the country), which has 3 more on the west side. Finally, on the left of that, one of the fiords of the south of the country is shown. It reminds the film Jurassic Park somehow.

In the second group of photos (figure **??**) it is possible to see a Kea parrot (a). This bird is kind of special because it is the only parrot specie that can live over 1800 m in the mountain. It is an endangered specie, and can only be found in that mountains of New Zealand. Next to that there is the Moeraki builders. This special almost spherical rocks are found in the east beached of the south island. They were of relevant religious importance for Maori villages of the area. Down to that picture, d, some seals can be seen laying in a rocky beach near the village of Kaikoura. They normally go there during the entire year and, at aroun May, they

(a) Kea parrot at Avalanche track

(b) Moeraki builders

(c) Pancake rocks

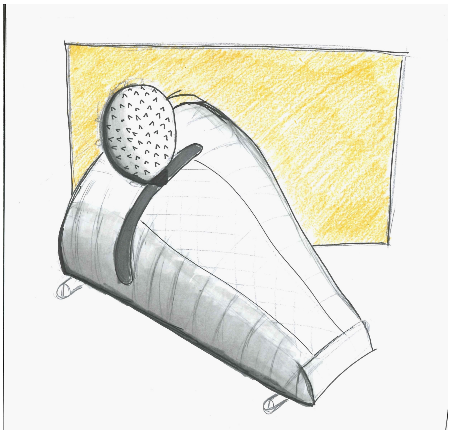
(d) Seals near Kaikoura

Figure 13.2: Second group of photos

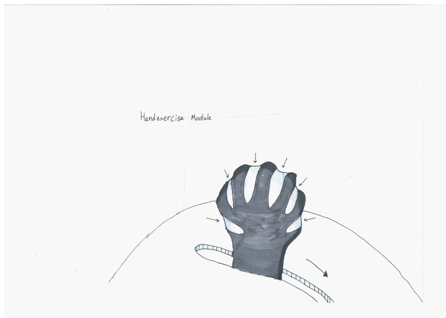
start mating at the small streams and rivers of the area. Finally, on the left, picture c, another rocky formation is shown. In that case this rocks, the Pancake rocks, are found in the west coast. Erosion and salt deposition made them look like a big group of pancakes put one on top of the other.

Appendix B: Hand Add-On non-selected pre-concepts

The non-chosen pre-concepts of that project are shown in the next figures. In figure **??**, it is seen the pre-concept number 1 generated in section **??**.



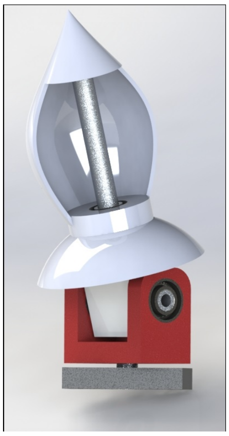
(a) Guide for P/S



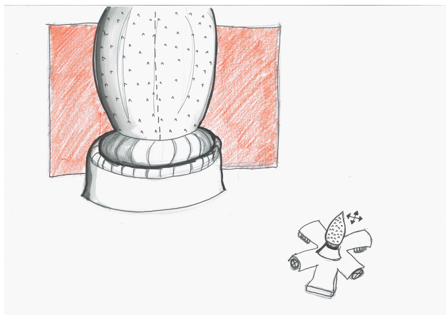
(b) Hand ball-like grasp

Figure 13.3: Pre-concept number 1: Guided P/S and ball-like grasp

Pre-concept number 2 is shown in figure **??**.



(a) Ball/cone-like structure



(b) Flat base for rotation

Figure 13.4: Pre-concept number 2: Ball/Cone-like grasp with flat base

Pre-concept number 3 is shown in figure **??** next page.

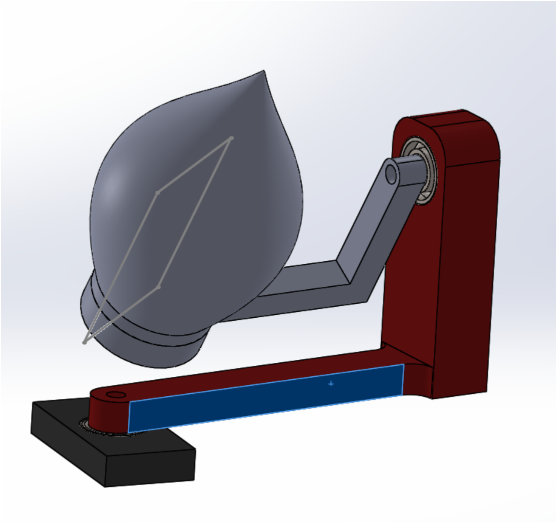
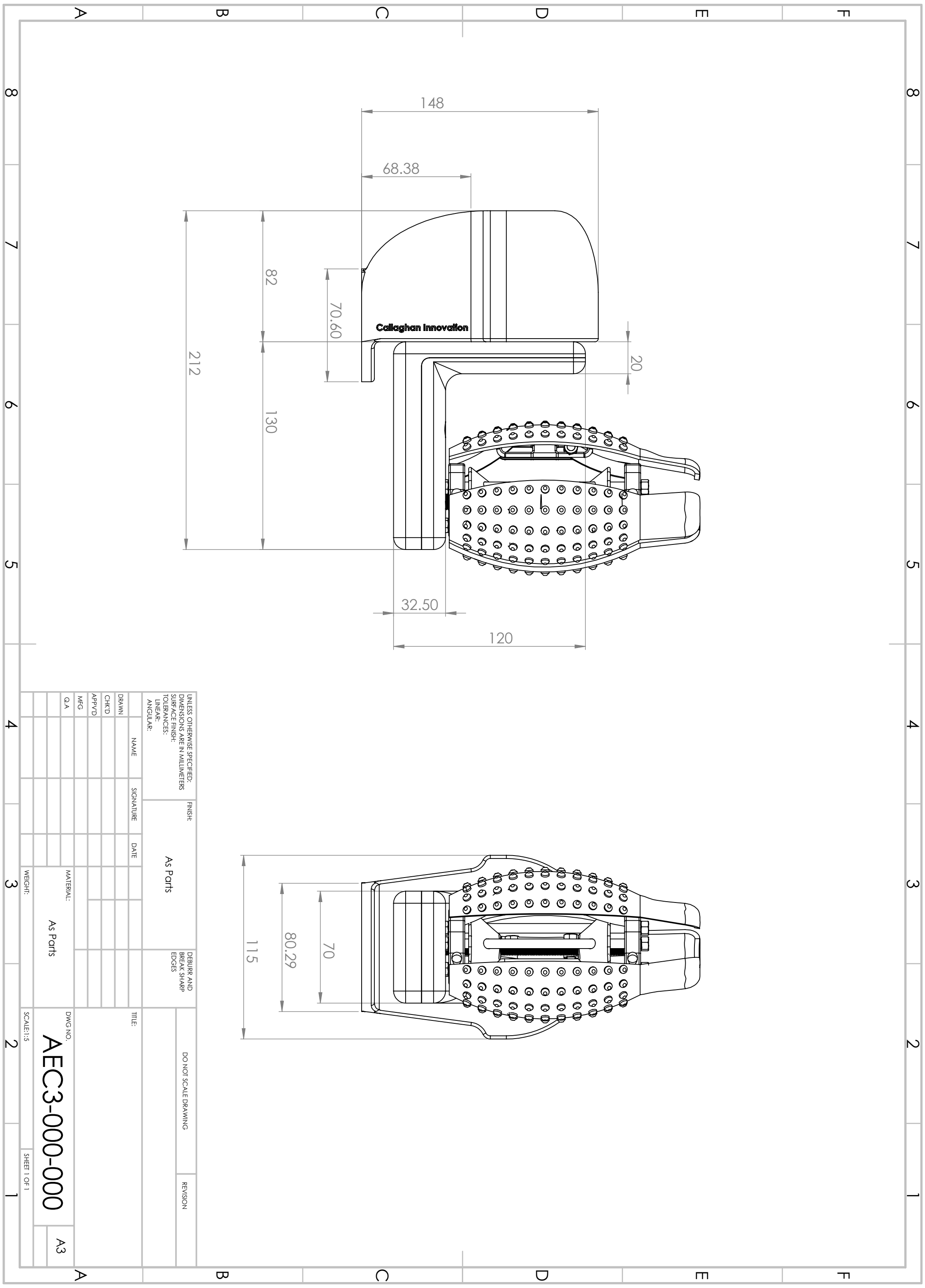
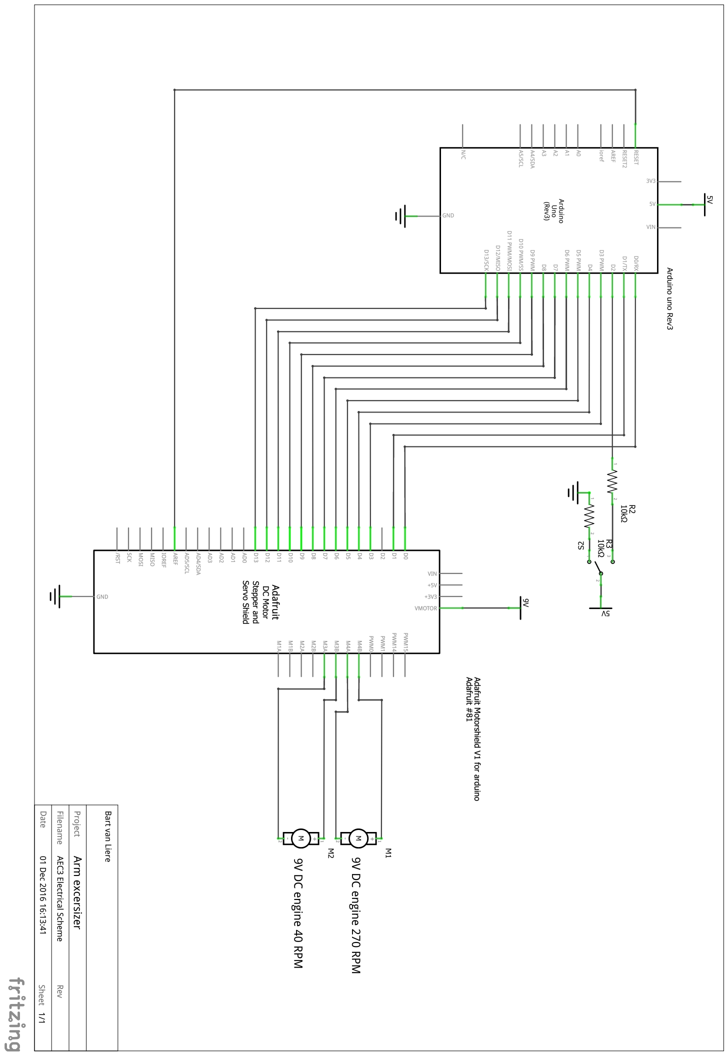


Figure 13.5: Pre-concept number 3: L-like base and cone grasp

Appendix C: Hand Add-On 1 Technical drawings



APPENDIX D: HAND ADD-ON 1 ELECTRICAL SCHEMATIC



APPENDIX E: HAND ADD-ON 1 BOM LIST

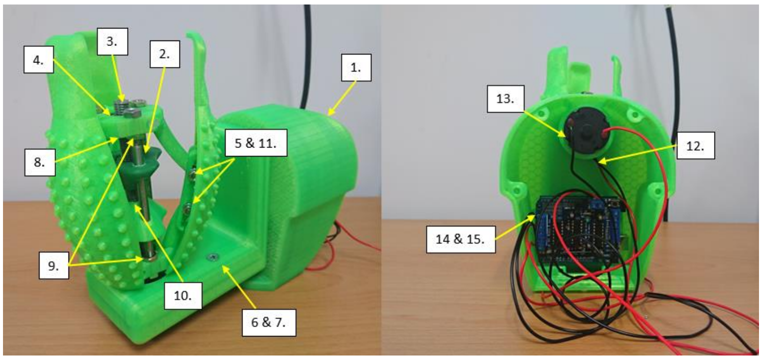
The final list of materials used for the first add-on device is shown here. The approximated final budget required to built it was 119 $.

BOM LIST – ADD ON 1

part	Company *	Part name	Description	Units **	Cost ***
1.	Own 3D Printer	3D Print	All our printed parts combined. +/- one roll of filament.	16 parts	$40
2.	Wakefield metals http://goo.gl/kvtegD	Unthreaded 6 mm shaft	Hand opening and closing cage. Structural part	-	-
3.	Wakefield metals http://goo.gl/kvtegD	Unthreaded 10 mm shaft	Hand opening and closing cage. Structural part	-	-
4.	NZ miniature bearings http://goo.gl/4geR5I	Bearing	Friction free movement of 10 mm shaft	2	$7.00
5.	Bunnings https://goo.gl/oXxBnJ	M4X15 mm CSK head bolt and nut	Fixing part	6	$5.88
6.	Bunnings	M5x19 mm CSK head bolt	Close the base	2	$6.16
7.	Anzor http://goo.gl/wgG3A6	Insert M5	Close the base	2	-
8.	Anzor https://goo.gl/q9Oqaj	Insert M10	Structural part	1	-
9.	Bunnings http://goo.gl/xJVYu1	Nut M6	Fixing part	12	$11.76
10.	Bunnings https://goo.gl/AZ17Oi	Nut M10	Structural part	1	$5.88
11.	Bunnings https://goo.gl/OGiYYB	Flat washer	Structural part	12	$6.22
12.	Ali Express	12V Worm gear motor	Drive the opening /closing of the cone	1	$16.59

	https://goo.gl/YE4OeK				
13.	Ali Express https://goo.gl/6fG8VE	12 Gear motor	Drive the pronation /supination move	1	$9.34
14.	Ali Express https://goo.gl/cXBUAO	Arduino Uno	Microcontroller	1	$8.51
15.	Ali Express https://goo.gl/vPP9kF	Motor shield	Connect the 12 V DC motors with the Arduino	1	$1.68

* Company and link where you can order it. (NOTE: Units does not correspond)
** Units that are only what inside or used in the Toy.
*** Costs are for ordering the whole package or lot and excl. shipping cost.



Appendix F: Hand Add-On 2 Technical drawings

The 2D and 3D technical drawins of this device are shown here.

Figure 13.6: 3D figure of the front/side view of the Add-On 1.

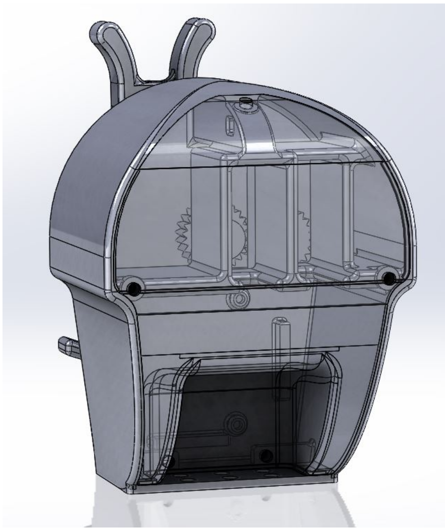
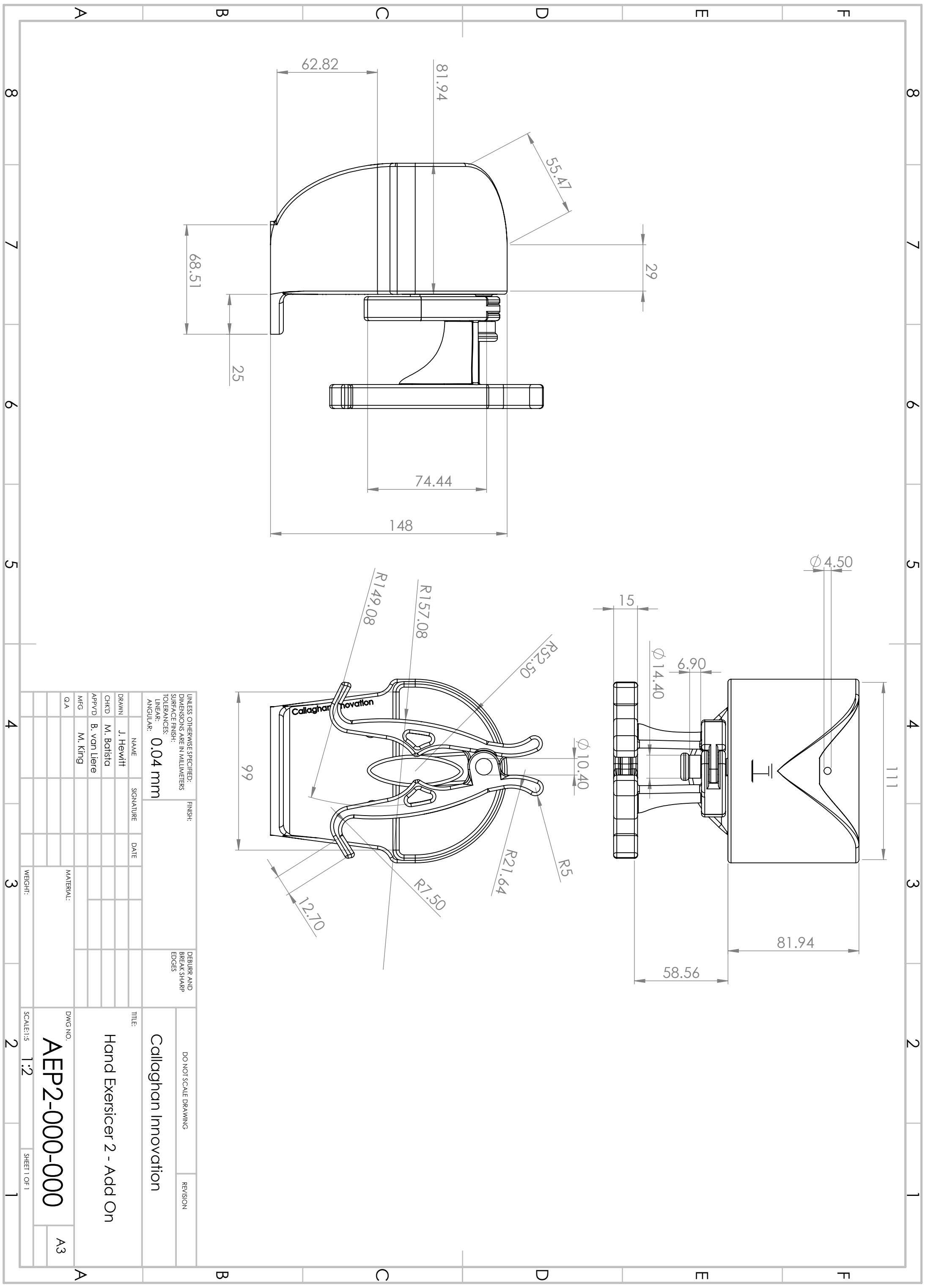


Figure 13.7: 3D figure of the back view of the Add-On 1.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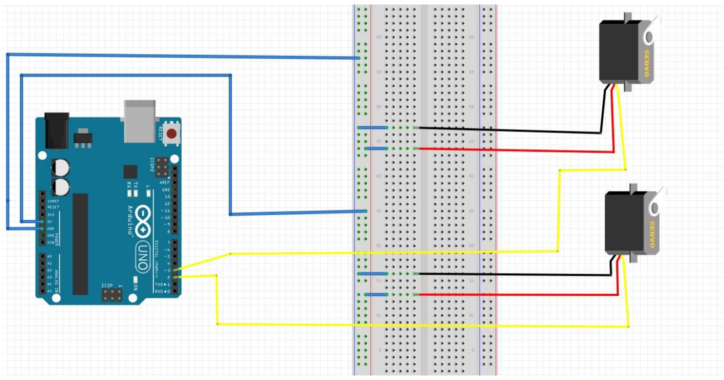
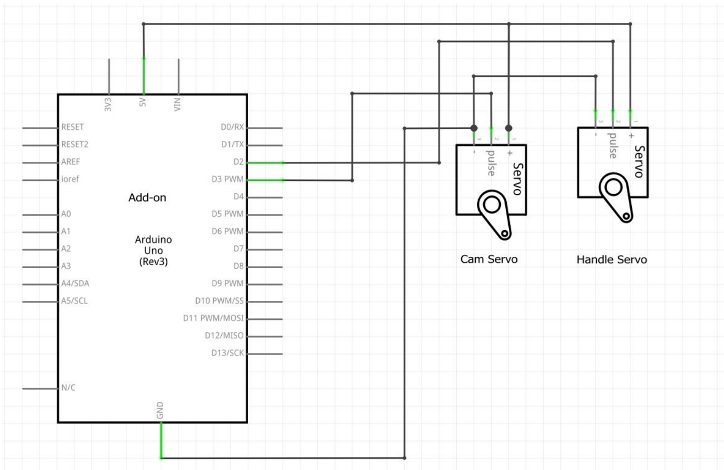
Callaghan Innovation

APPENDIX G: HAND ADD-ON 2 ELECTRICAL SCHEMATIC

The final drawings of the electrical schematics of Add-On 2 are found here. It is mainly about the conection of both motors with the microprocessor that controls their movement.





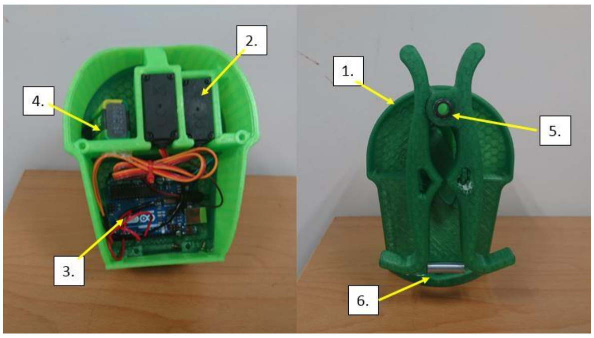
APPENDIX H: HAND ADD-ON 2 BOM LIST

The final list of the materials required to build the second add-on device is shown here. The approximated costs on that case were 115 $.

BOM LIST – ADD ON 2

part	Company *	Part name	Description	Units **	Cost ***
1.	Own 3D Printer	3D Print	All our printed parts combined. +/- one roll of filament.	11 parts	$20
2.	Ali Express https://goo.gl/elLjGx	Servo motor	Motors to drive the device (opening /closing and pronation /supination)	2	$49.98
3.	Ali Express https://goo.gl/cXBUAO	Arduino Uno	Microcontroller	1	$8.51
4.	Bunnings https://goo.gl/QrXfca	Battery 9V	Power the motors	1	$7.88
5.	Ali Express https://goo.gl/Sk51SI	Bushes	Reduce friction between the handles	1	$3.99
6.	Jaycar https://goo.gl/WX2bvi (Box full)	Tension spring	Springs to return the function to their start position.	1	$24,90

* Company and link where you can order it. (NOTE: Units does not correspond)
** Units that are only what inside or used in the Toy.
*** Costs are for ordering the whole package or lot and excl. shipping cost.



APPENDIX I: TOY TECHNICAL DRAWINGS

In this Appendix, all 2D and 3D technical drawings and view of the Toy are detailed. The 2D front, back and side view of the Toy is shown. Also an schematic 2D view of the inside of the Toy was done. All the figures were obtained with Solidworks 2016 CAD design program.

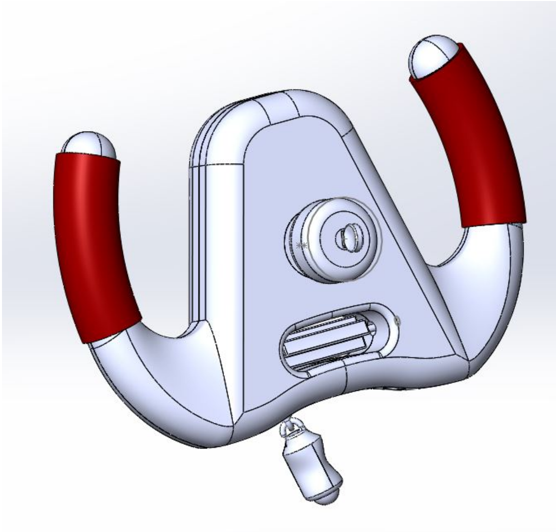


Figure 13.8: 3D figure of the front view of the Toy.

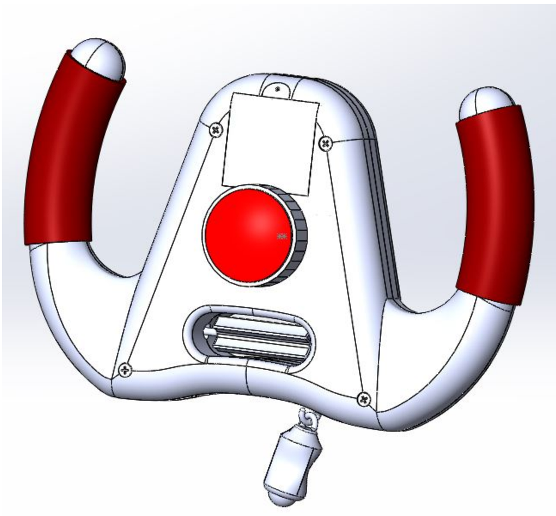
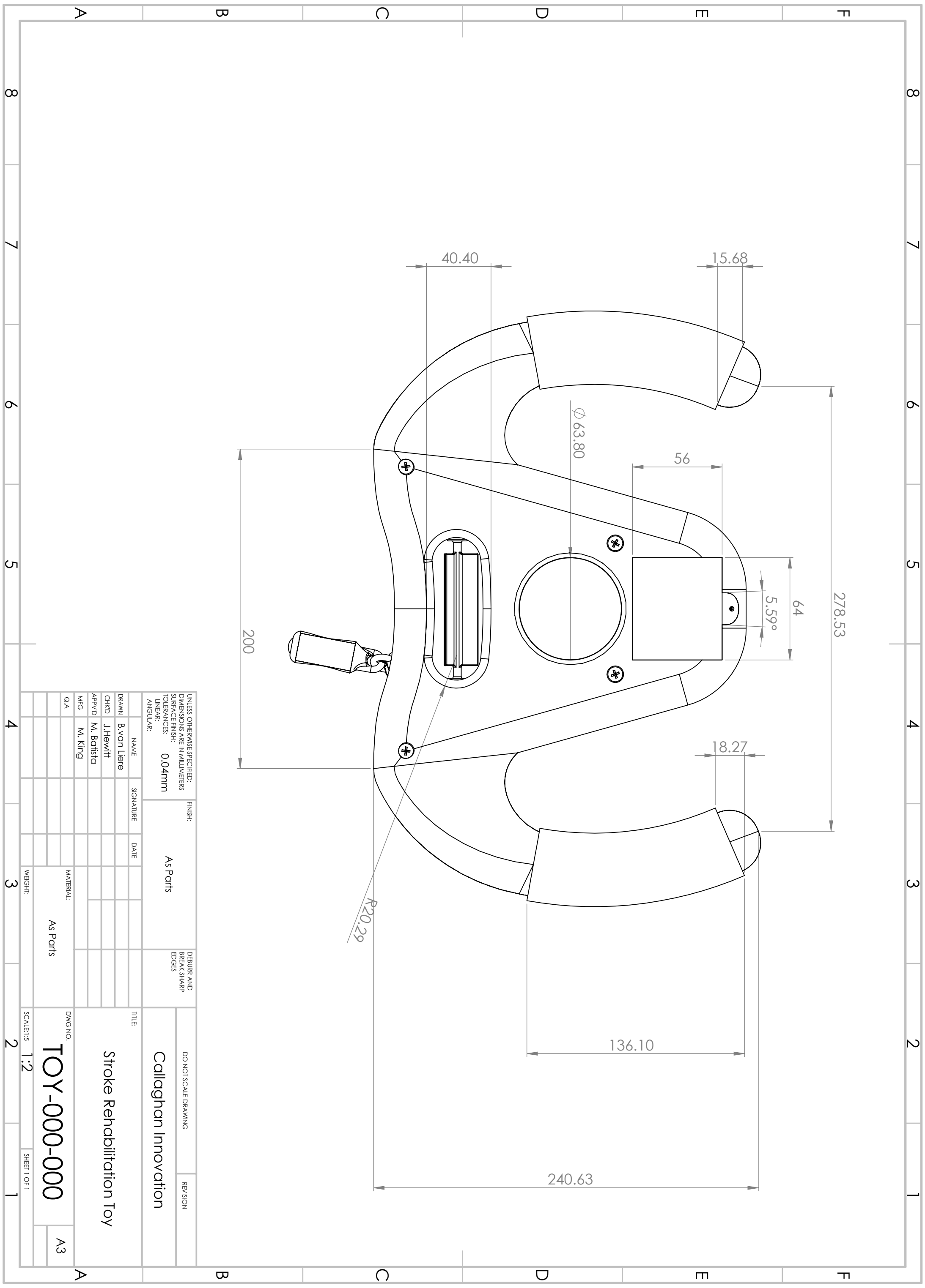


Figure 13.9: 3D figure of the back view of the Toy.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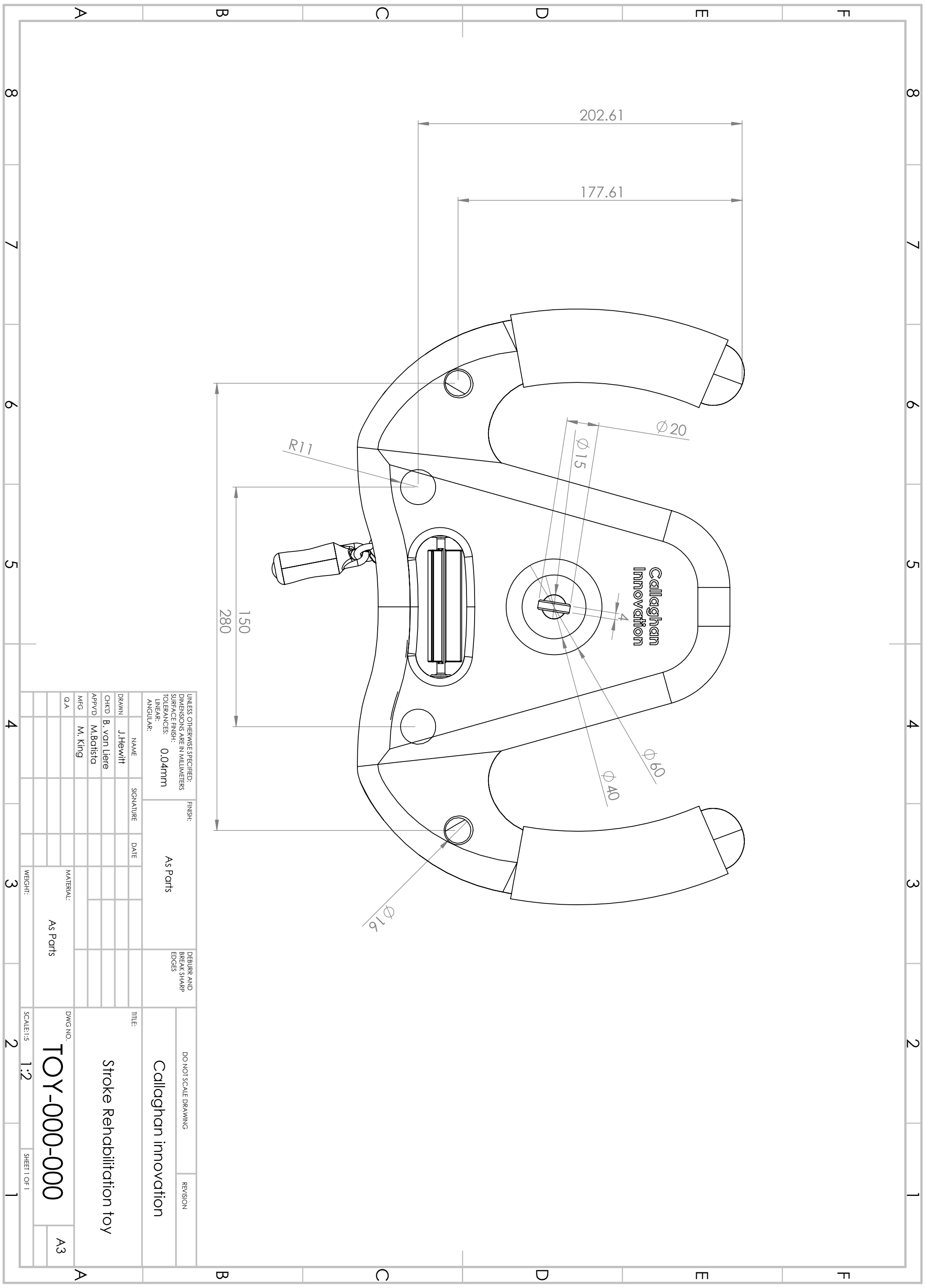

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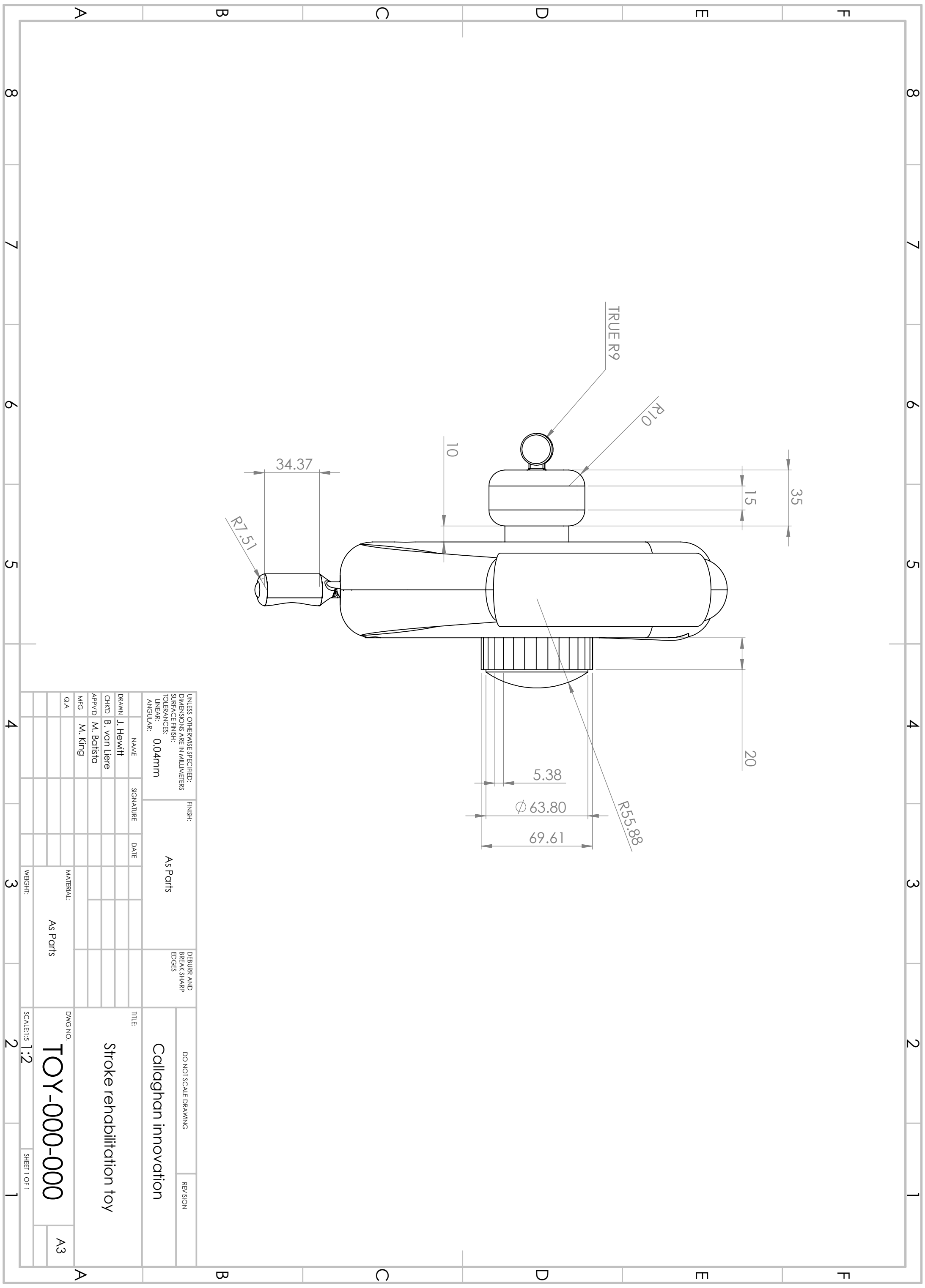
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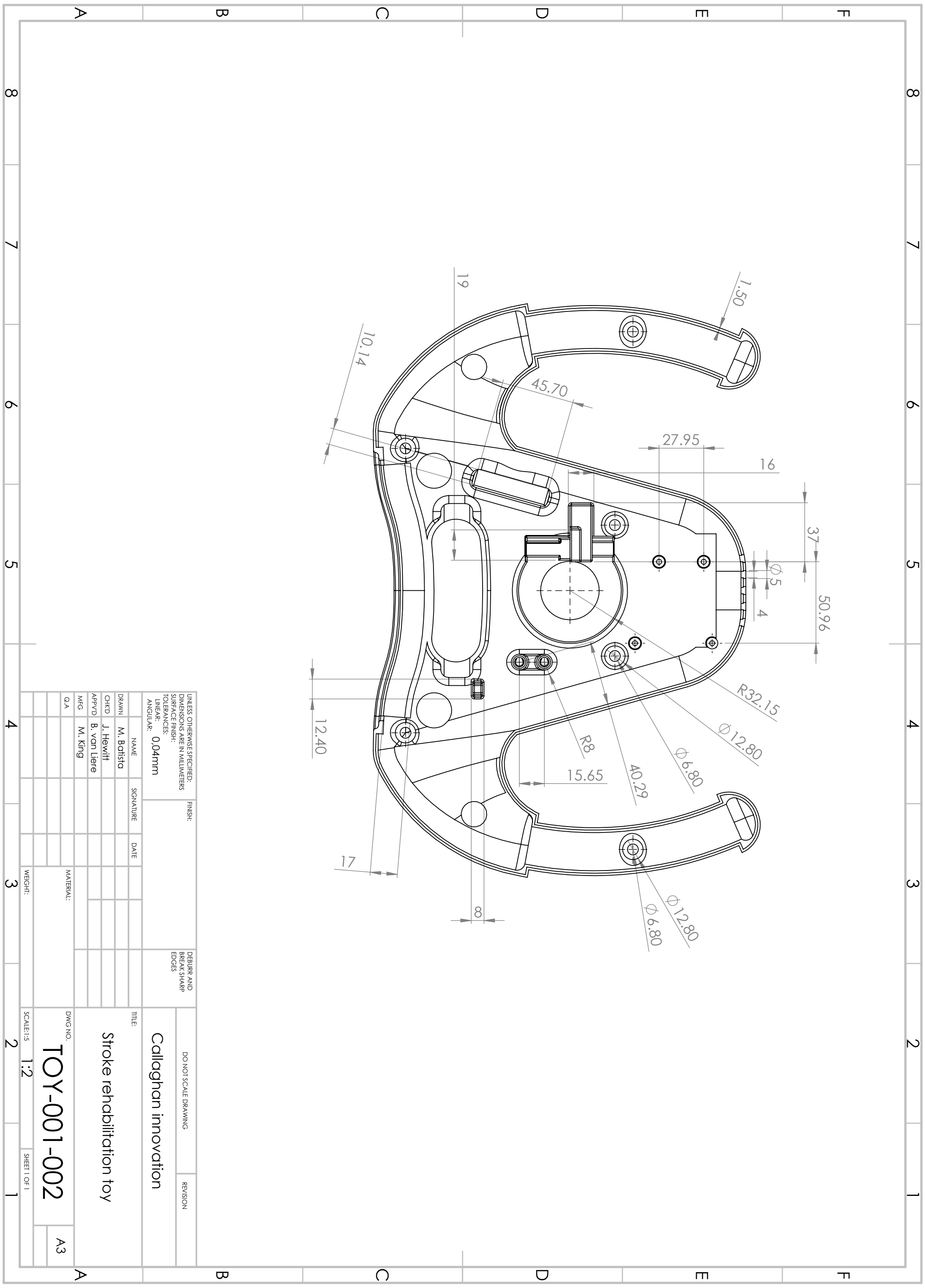
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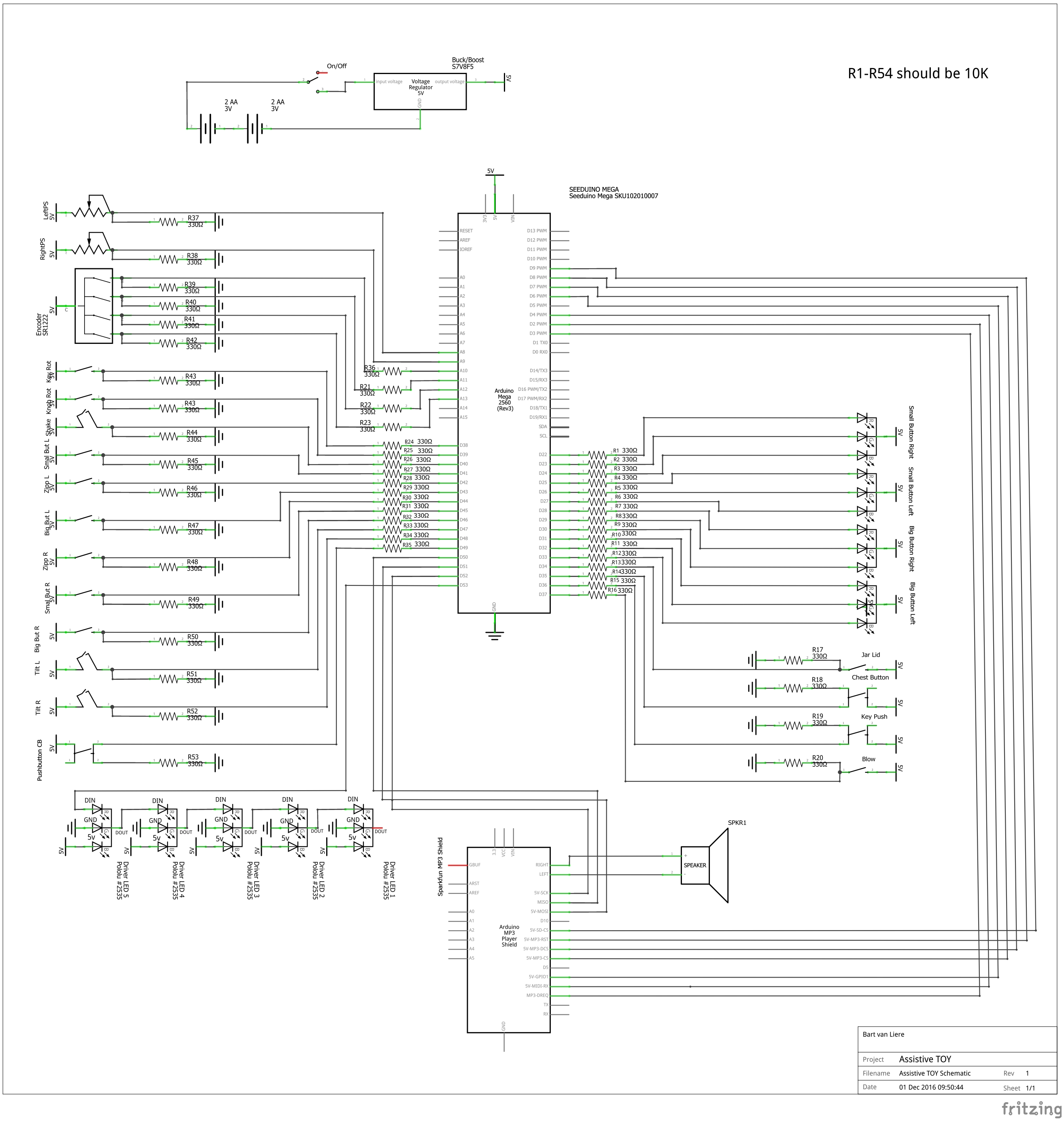
APPENDIX J: TOY ELECTRICAL SCHEMATIC

The electrical scheme shown here was built with the schematic program Fritzing. All components and electric elements were obtained from there.



APPENDIX K: TOY BOM LIST

In this section, the bill of materials (BOM) list is shown. The final budget for this device was approximately 340 $. This price makes the final product affordable by the user/patient.

BOM LIST - TOY

part	Company *	Part name	Description	Units **	Cost ***
1.	Own 3D Printer	3D Print	All our printed parts combined. +/- one roll of filament.	14 parts	$40
2.	**Ali Express** https://goo.gl/oWIuR0	Insert M5	Inserts to close the toy.	9	$10,13
3.	Bunnings http://goo.gl/GR79i6	Screw M5x25 CSK head	Screws to close the toy.	5	$6,16
4.	**Bunnings** http://goo.gl/ZfQiTP	Screw M5x38 CSK head	Screws to close the toy.	4	$6,16
5.	Ali Express https://goo.gl/ybf6cE	Foam 10mm	Foam to cover the handles.	4	$35,50
6.	Bunnings https://goo.gl/IXk1MI	Batteries AA 1,5V	Batteries to power the toy.	4	$9,98
7.	Jaycar https://goo.gl/WX2bvi (Box full)	Tension spring	Springs to return the function to their start position.	3	$24,90
8.	Seeeduino https://goo.gl/ol6LV8	Seeeduino	Microcontroller	1	$43,00
9.	Nicegear https://goo.gl/Lhq6VG	Sparkfun mp3-Shield	Mp3 shield to play mp3 audio files.	1	$45,00
10.	-	SD card	SD card to save the mp3 audio files.	1	$
11.	Nicegear https://goo.gl/UETBKK	Voltage regulator Polulu 5V Step up/down	Voltage regulator to regulate the amount of voltage from the batteries.	1	$8,00

12.	Ali Express https://goo.gl/ZqKTGG	Micro switch	Micro switch to detect the movement of each function.	5	$5,80
13.	Nicegear https://goo.gl/Qgz51Q	Push button switch	Push button switch to detect the movement of the pull or push movement.	2	$2,00
14.	Ali Express https://goo.gl/OCT1kc	Force sensitive resistor	Sensor to detect the squeeze of the handles.	2	$31,80
15.	Ali express https://goo.gl/MuQRLn	Vibration sensor	Sensor to detect the shake action.	1	$1,65
16.	Ali Express https://goo.gl/mld32r	Tilt sensor	Sensor to detect the steering action.	2	$0,76
17.	RS https://goo.gl/AV41Ca	Reed switch	Sensor/switch to detect the blow action.	1	$9,01
18.	Ali Express https://goo.gl/b0VJqQ	Resistors 10K	Resistors to regulate the amount of voltage and amperes.	59	$1,44
19.	-	Electrical wires	Wires to connect all the inputs/outputs together.	-	$
20.	**Polulu** https://goo.gl/UDxnDV	RGB LED's	LED's to	5	$4,45
21.	Ali Express https://goo.gl/qUd5rK	Speaker 8 Ohm, 2 Inch	A speaker to play the mp3 files.	1	$11,58

22.	Ali Express https://goo.gl/vZDE6A	LED Push button 16mm 6V.	Two small push buttons with a LED inside.	2	$13,05
23.	Ali Express https://goo.gl/nDHBwK	LED Push Button 22mm 6	Two big push buttons with a LED inside.	2	$23,16
24.	Ali express https://goo.gl/2VrAX2	Toggle switch	To switch the toy on/off.	1	$1,57
25.	Jaycar https://goo.gl/76eBxN	Binary encoder	To select the difficulty level.	1	$4,90

* Company and link where you can order it. (NOTE: Units does not correspond)
** Units that are only what inside or used in the Toy.
*** Costs are for ordering the whole package or lot and excl. shipping cost.