

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

A Smart Device For Hand Rehabilitation

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Abstract

Hand rehabilitation plays a crucial role in aiding recovery and promoting functional independence for individuals with hand disabilities, such as stroke victims, multiple sclerosis patients, and prosthetic users. This dissertation discusses the research and development leading to a prototype designed to enhance therapy for patients struggling with Activities of Daily Living.

This prototype reinterprets the SHaRe project from the Faculty of Engineering of the University of Porto, utilizing hand compression force for controlling rehabilitation-oriented games. Gamification plays a vital role in motivating patients to regain control over their affected hand's strength.

The development focused on creating an alternative hand grip training system without sacrificing resolution, resulting in a 3D printed load cell with two optical sensors, offering a new solution to challenges identified in SHaRe.

A custom-made Printed Circuit Board (PCB) was developed for this project, along with firmware for the cup's microcontroller (an ESP32) using the Arduino IDE.

A "Serious Game" for Android devices was also created, featuring three mini-games targeting different aspects of hand force control, operated with the new device.

Rehabilitation specialists were involved in the prototype's evaluation process, providing valuable feedback. Their expertise helped assess usability and effectiveness in a clinical setting, revealing promising results for this new prototype. By retaining the cup form of its predecessor, the new device can be easily integrated into rehabilitation sessions focused on daily activities.

Keywords: Hand Rehabilitation, Gamification, Cost-Effective Measurement System, Plastic Load Cell, Optic Sensors, Occupational Therapy.

Resumo

O processo de reabilitação da mão desempenha um papel vital no auxílio à recuperação e na promoção da independência funcional de indivíduos que sofrem de deficiências na mão, nomeadamente vítimas de acidente vascular cerebral (AVC), pacientes com esclerose múltipla e pacientes que usam prótese de mão. Esta dissertação descreve a pesquisa e o desenvolvimento que levaram à criação de um protótipo para promover a terapia de pacientes com dificuldades na realização de atividades manuais do dia-a-dia.

Este protótipo é uma reinterpretação do projeto SHaRe da Faculdade de Engenharia da Universidade do Porto, um sistema que faz uso da força de compressão da mão para o controlo de jogos feitos para reabilitação. A *gamificação* tem aqui um papel fulcral como força motivadora, ao incentivar o paciente a recuperar o controlo da força na sua mão afetada.

O trabalho de desenvolvimento centrou-se na criação de um sistema de treino de força de compressão da mão alternativo sem comprometer a resolução do dispositivo, concretizando-se na criação de uma célula de carga impressa equipada com dois sensores ópticos, proporcionando uma solução nova para os problemas levantados no SHaRe.

Uma placa de circuitos (**Printed Circuit Board (PCB)**) personalizada foi desenvolvida especificamente para este projeto, juntamente com o firmware para o microcontrolador do copo (um ESP32) utilizando o **Integrated Development Environment (IDE)** do Arduino.

Foi também feito um "Serious Game" para dispositivos Android, que inclui três mini-jogos orientados para diferentes aspetos do controlo de força da mão, controlados com o novo dispositivo.

Especialistas em reabilitação estiveram envolvidos no processo de avaliação do protótipo, oferecendo *feedback* valioso. A sua experiência ajudou a determinar a usabilidade e eficácia num ambiente clínico, revelando o carácter promissor deste novo sistema. Ao manter o formato de um copo do seu antecessor, é possível o novo dispositivo ser facilmente incorporado em sessões de reabilitação orientadas à realização de atividades do dia-a-dia.

Palavras-chave: Reabilitação da Mão, Gamificação, Sistema de Medição Económico, Célula de Carga de Plástico, Sensores Ópticos, Terapia Ocupacional.

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Rui Miguel Samúdio

*“Run, rabbit, run
Dig that hole, forget the sun
When, at last, the work is done
Don’t sit down, it’s time to dig another one”*

Roger Waters

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Abbreviations

- ABS** Acrylonitrile Butadiene Styrene. xi, 28–32, 34
- ADC** Analog-to-Digital Converter. 35–37
- ADHD** Attention Deficit and Hyperactive Disorder. 10
- ADL** Activities of Daily Living. 1, 8
- BCI** Brain-Computer Interface Technology. 6
- BLE** Bluetooth Low Energy. 36, 37, 40, 41, 47, 62
- CPU** Central Processing Unit. 36, 37
- EEG** Electroencephalogram. 6
- FES** Functional Electrical Stimulation. 6, 8
- fMRI** Functional Magnetic Resonance Imaging. 6
- FNIRS** Functional near-infrared spectroscopy. 6
- GPIO** General Purpose Input/Output. 36, 37
- HGTD** Hand Grip Training Devices. 7, 8
- IDE** Integrated Development Environment. iii, 35–38, 43
- IMU** Inertial Measurement Unit. 7, 15, 17, 62
- IoT** Internet of Things. 8, 36
- LED** Light Emmiting Diode. 37, 38
- MEG** Magnetoencephalography. 6
- PCB** Printed Circuit Board. iii, xi, 30, 31, 35, 37, 38, 43, 51, 53
- PET** Polyethylene terephthalate. 34, 62
- PETG** Polyethylene Terephthalate Glycol. 28, 31–34, 57, 61

PLA Polylactic Acid. 51, 62

PSBR Physiological Signal-Based Rehabilitation. 6, 7

SHaRe System for Hand Rehabilitation in Dexterous Manipulation of Daily Objects. xi, 1, 2, 5, 7, 9, 13, 15–19, 21, 29, 52, 53, 55, 57, 58, 60–62

SUS System Usability Scale. xiii, 55, 56, 58–60, 62

UEQ User Experience Questionnaire. xii, 55, 56, 58–60, 62

UI User Interface. 6, 9, 13, 47

Chapter 1

Introduction

In the domain of medical rehabilitation, technological advancements have made substantial contributions to improve the quality and effectiveness of treatment procedures, particularly in the area of upper limb rehabilitation. It's a field that has seen a plethora of research and development initiatives focused on devising instrumented devices to enhance rehabilitation efforts. The Laboratory of Instrumentation for Measurement at the University of Porto and the University of Porto have also been involved in this particular field since 2014 with several different prototypes, such as the **SHaRe** [1], the Lipowise [2] and the Gripwise [3]. Later, the technology transfer of health devices to the UPorto spin-offs Gripwise Tech and Wisify complemented and projected those efforts. Nowadays, the Gripwise system has also expanded to the areas of rehabilitation and occupational therapy. The spin-off company Gripwise Tech is currently supporting the evolution of the **SHaRe** prototype.

The **SHaRe** prototype represents a compelling integration of detailed and novel mechanical parts design, sensors, signal conditioning, communication technologies and interactive software to provide a more patient-centered and engaging therapeutic platform for patients presenting difficulties in **Activities of Daily Living (ADL)** [4]. The original system developed in 2014 comprises an instrumented device designed in the shape of an everyday object, specifically a cup, which measures the force applied by the user when handling it, and a software application. The measured data in the device is transmitted to a computer where a specially designed program provides visual feedback on the applied force [1]. However, the system has its limitations and areas for further enhancement. This has led to the need for revisiting the device in order to explore the possibility of incorporating a new sensing solution and introducing new communication capabilities.

1.1 Context and Motivation

The need to refine and improve **SHaRe** is fueled by a dual objective: to increase the system's efficacy in aiding hand rehabilitation and to enhance its usability for the patients and therapists. By

exploring alternative sensors, load cell designs and materials, the project aims to provide a potentially cheaper product while improving on **SHaRe**'s shortcomings, thus increasing its therapeutic value.

Similarly, introducing new communication capabilities, particularly Bluetooth connectivity, could make the system more user-friendly and versatile, enabling operation with various devices such as smartphones or tablets.

1.2 Objectives

This project sets out to perform and document the following tasks:

- Selection and Development of a new sensing system for the prototype;
- Implementation of a microcontroller for data acquisition, processing and *Bluetooth* communication;
- Development of a user interface that provides the patient with visual feedback on their hand force while manipulating the device;
- Creation of a functional prototype;
- Conducting validation tests of the developed solution.

1.3 Structure

This thesis is comprised of 8 chapters.

The first chapter, **Introduction**, serves as an overview of the project's motivations and objectives.

The second, known as the **Literature Review**, aims to examine the current advancements in the field of hand rehabilitation, presenting an overview of commercially available devices and exploring the concept of gamification and serious games in therapeutic environments.

The third chapter goes over the predecessor of the subject matter addressed in this thesis, the **SHaRe**, highlighting its benefits and limitations, while providing a bridge between the Literature Review and the Development stage.

The fourth chapter, **Selection and Development of a New Sensing System**, explores the process that led to the new sensing solution implemented in the developed prototype.

The fifth chapter, **Implementation of a Microcontroller System with Bluetooth Connectivity** delves into the selection of the electronic components that comprise the prototype's communication solution, while also providing some insight on the created firmware and its functionalities.

The sixth chapter of the development process, **User Interface Incorporation** provides an overview on the creation of an android-based serious game in the Unity Engine, supplying the prototype with a gamified approach to hand rehabilitation.

Chapter 7, **Assembly, Validation Tests and Findings**, explores the prototype's mechanical design and final assembly, while also providing the results of the validation tests conducted with health-care professionals.

Finally, Chapter 8, **Conclusions and Future Work** goes over the findings and concludes the thesis while also providing some insight on the necessary developments in this field.

Chapter 2

Literature Review

The proposal that inspired this dissertation was to improve on aspects of the **SHaRe** prototype, a hand rehabilitation device developed in the Laboratory of Instrumentation for Measurement of the Faculty of Engineering of the University of Porto.

Occupational therapy and Physiotherapy play a crucial role in the rehabilitation of patients that have lost the capacity to perform daily activities. However, it sometimes takes years of heavy therapy and high motivation for the patient to regain the necessary motor skills, which can be a very frustrating and painful process. As such, the industry is attempting to lighten the load and increase patient compliance by *gamifying* physiotherapy, making the experience more interactive and engaging while recording the necessary data to analyse the person under care. This has the ability to be helpful for both the care recipient and their therapist, as it helps the patient stay focused and motivated whilst their evolution is being tracked.

As such, there appears to be a growing number of studies relating the use of embedded devices in a therapy setting with the added benefits of therapy's *gamification*.

There has been a significant increase in the availability of different commercial devices for hand rehabilitation with a gamified approach, resulting in more options for both therapists and patients.

2.1 Overview of Hand Rehabilitation Devices

A contact-type device for hand rehabilitation is a device that is required to be in contact with the patient's injured hand with the purpose of aiding therapeutic processes. This literature review will be focused on devices that collect data through the use of sensors. These devices can vary in the kind of data they collect and their ultimate goal: there are Hand Rehabilitation Robotic Devices, which provide assistance in the movements of the hand and fingers, Physiological Signal-Based Robots, who collect physiological data to improve therapy, data gloves, that record hand movements and finger flexion, Hand dynamometers adapted for rehabilitation purposes and Hand Grip Training Devices to improve fine motor control.

2.1.1 Robotic Devices

As a reliable and effective method for improving hand impairment, robotic-assisted training involves the use of computer-driven robots in order to provide repetitive exercises, which can stimulate neuroplasticity. According to *Qu et al.* [5], robotic devices can be categorized as exoskeletons, end-effectors and orthoses. Exoskeletons are able to perform long-term tasks that require repetitive movements, ensuring the intensity, effect, and accuracy of rehabilitation training, having a good movement consistency. End-effector devices, in contrast, are controlled by the distal interphalangeal joint and are primarily designed for finger rehabilitation. Orthoses typically use flexible gloves as carriers and are more focused on finger movements, but lack actuators and sensors [5].

2.1.2 PSBR

Physiological Signal-Based Rehabilitation (PSBR) is defined by the use of physiological signals, like brain activity, muscle activity, and sensory feedback, in order to control rehabilitation devices, such as robots or electrical stimulation devices, as to improve hand function in patients. This type of rehabilitation offers training that can benefit patients who are unable to actively participate in traditional rehabilitation methods due to severe motor deficiencies.

There are several categories of physiological signal-based rehabilitation:

- **Brain-Computer Interface Technology (BCI)** is one category that enables direct conversion of a patient's brain activity into an external device without the participation of peripheral nerves and muscles, which can be combined with other technologies, such as robotic devices or visual feedback technology, in order to complete the neural circuit from signal sending to receiving.
- **Functional Electrical Stimulation (FES)** directly activates muscles to perform functional tasks by applying appropriate and precise electrical stimulation through an auxiliary electrical stimulation device, which can be helpful in recovering hand function in patients.
- Hybrid Systems combine multiple senses (such as tactile, visual and auditory) and physiological signals (from **Electroencephalogram (EEG)**, **Magnetoencephalography (MEG)**, **Functional Magnetic Resonance Imaging (fMRI)** and **Functional near-infrared spectroscopy (FNIRS)**) to enhance brain command decoding.

Most devices in this category combine multiple areas of expertise. Such is the case of the *Ipsihand* [6], which combines wearable robotic devices with an EEG based-biometric headset and a tablet computer to provide a **User Interface (UI)**, making it the first commercially approved **BCI** device. In a 2023 article by Gao et al. [7], a hand rehabilitation device that couples **BCI** with Virtual Reality has also shown great promise in this field by enhancing the test subjects' hand motor recovery.

Overall, **PSBR** is a promising field that offers new possibilities for improving hand function in patients who have suffered from a stroke. By using a combination of advanced technologies

and techniques, rehabilitation professionals can enhance the interaction between patients and machines and provide more effective and efficient rehabilitation interventions. However, the nature of these systems makes **PSBR** less suitable for home therapy, as it entails expensive technology that cannot be handled by the patient alone, requiring, as such, the involvement of technicians and/or therapists.

2.1.3 Instrumented Devices

In the context of hand rehabilitation, an instrumented device is a device equipped with sensors to aid in the rehabilitation process, typically implemented alongside a virtual environment (most instrumented devices are used in the hand rehabilitation field to control Serious Games [4, 8]). These devices can be developed for training in hand and finger movement, in the case of Data Gloves, or for Grip training and fine motor control (such as Hand Dynamometers and **Hand Grip Training Devices (HGTD)**). Overall, instrumented devices are simple and portable hand rehabilitation solutions [8], making them the most adequate for home therapy without the need of a supervising therapist.

2.1.3.1 Data Gloves

Data gloves have seen a rapid development in recent years, as they can provide objective range of motion information useful for clinical hand assessment and rehabilitation. These wearable devices contain sensors to track hand and finger movements. They capture the motion of the user's hand and fingers, providing information to control computer applications and analyse the patient's data.

A data glove consists of a number of sensors that read the position of the fingers and hand at any given time. Most mainstream data gloves use fiber optics to measure each finger's joint range of motion, but this information can also be provided via Hall-Effect sensors or piezoresistors. They can also include an **Inertial Measurement Unit (IMU)** to provide hand orientation data.

One of the first data gloves to be commercially released was the Power Glove (Figure 2.1) in 1989, an accessory for the Nintendo Entertainment System which was conceived to allow for a more immersive gaming experience, using the entire hand to play a game instead of a controller [9]. The original prototype was adapted from the first data glove patent, using the same optic flex sensor based sensing solution [10], allowing for precise movement capture, although this solution was eventually replaced for a less expensive carbon-based flex sensors in mass production. This led to the final product being considered imprecise and complicated to set up, requiring some time to calibrate [11], and thus was ultimately a commercial failure. The Power Glove exemplifies the trade-off between cost reduction and maintaining usability in sensing solutions, a key consideration in developing the new **SHaRe** prototype. While aiming for affordability, the prototype, like the Power Glove, functions as both a hand rehabilitation device and a game controller, highlighting the importance of not compromising on usability.

Even though data gloves have been available to the public since the 1980's, there has been a recent increase in interest in the research and development of these devices due to their potential



Figure 2.1: Power Glove

applications in the field of hand rehabilitation, particularly in home-based settings. Some examples of recent commercial data gloves are the HandTutor [12], which can be combined with FES to improve fine hand motor skills, the RAPAEEL Smart Glove [13], which offers more than fifty serious games, and the Music Glove [14], which uses music as an interactive medium. The Music Glove, despite being the simpler and less expensive of these examples (while HandTutor and RAPAEEL are worth 1000\$ and 18000\$, the Music Glove is sold at only 370\$), has been proven to keep the patients engaged and motivated with its music-based interface (very reminiscent of the videogame Guitar Hero [15]) while improving hand function.

2.1.3.2 Hand Grip Training Devices and Hand Dynamometers

Although Hand Dynamometers have been a common staple of hand therapy since the late 1970's [16], the measurement of grip strength has turned out to be of wide-ranging importance. Since then, thousands of articles have been exploring the correlation of grip strength with many other physical conditions becoming an important physical-condition indicator. Meanwhile, recent developments in Microcontrollers and IoT applications have allowed a growth in commercially available grip strength measurement devices with data acquisition for therapeutic purposes.

A hand dynamometer is a tool that measures isometric grip force (hand grip strength). Some versions use hydraulics to measure the force while others, especially Internet of Things (IoT) hand dynamometers, use electronic load cells. The function of a hand dynamometer is to assess the user's grip strength [17], making it an evaluation tool rather than a device for aiding rehabilitation. By providing real-time data about a user's grip strength while also implementing training procedures, Hand Grip Training Devices have become increasingly common in therapeutic applications [18]. Most HGTDs, such as the Pablo [19], Gripwise [3] and GripAble [20], are focused on assessing and training grip strength. However, for patients with neurological conditions, such as stroke victims, or with myoelectric prosthetic limbs, the therapeutic needs differ from the training these devices provide. As such, there is a need to fill in this void with devices focused on fine grip force control, in order to help patients with ADL. Even though these devices have existed in academic studies for the last twenty years [21, 22], commercial devices are still scarce, and most developed fully integrated systems were produced for testing in academic environments (like the

Gr!pp system [23] from the University of Twente and the SHaRe system [1] from the University of Porto).

In all the aforementioned devices (figure 2.2), the focus is to take physical therapy to patients homes, and, as such, to provide a simple UI to train the patient. This is achieved by assuring communication between the device and a mobile application that is designed specifically to keep the patient motivated in their training while also providing valuable data for therapists to track the subject's progress. In most use cases, *gamification* has been found to be the method to create an UI more associated with increased patient compliance in the rehabilitation process, which is essential as effective therapy must be intense and requires the continuous repetition of relevant functional tasks [24].



Figure 2.2: Hand Dynamometers (a and b) and Hand Grip Training Devices (c and d)

2.2 Gaming as a Motivational Tool

As seen in the previous section, a gamified approach to hand rehabilitation has often been used with positive results for the patient, as it led to increased motivation and engagement. As this thesis' main project includes the creation of a UI that involves the gamification of the rehabilitation process, it's important to analyse how gamification works and its place on hand rehabilitation.

2.2.1 Gamification and Serious Games

Even though the term "Gamification" has only emerged recently, with the game designer Nick Pelling coining the term in 2002 [25], the concept has been alluded to for centuries. For example,

Plato wrote extensively about how games could provide a great method of educating children to become knowledgeable adults [26].

Gamification is the process of adding game-like elements to non-gaming activities, gaining notoriety in the XXI century as a powerful engagement tool [25]. Any activity could be, in theory, gamified, as long as it uses some game mechanics, such as:

- Reward Systems;
- Challenges to Overcome;
- Achievements;
- Punishment;
- Score Systems.

With the emergence of Smartphones and mobile gaming, learning apps like Duolingo [27] and Memrise [28] have taken advantage of these game mechanics to present a compelling and essentially addictive [29] way for users to learn a new language. Other platforms like Coursera and Khan Academy use level-based progression and reward systems to keep the user engaged in their courses. Some schools have even started to advertise themselves as gamified approaches to learning, like the 42 Network [30].

As game-like applications became more popular, a parallel branch that personifies the attributes of gamification emerged in the form of Serious Games: fully fledged games developed for purposes other than entertainment [31]. In the healthcare context, most early serious games' target demographic were children, and have been found to greatly contribute to the engagement and motivation of children with **Attention Deficit and Hyperactive Disorder (ADHD)** [32]. This paradigm started to change with the release of Nintendo Wii in 2006, a low-cost motion based game console [33] that included several games that promoted physical activity. The game Wii Sports Bowling has been found to induce a flow-like state in elderly participants that found it easier and more engaging than actual bowling [34], and Wii Fit has also been applied to occupational therapy, with reports pointing to improvements in older adults' quality of life [35] (figure 2.3).



Figure 2.3: Elderly Person using Wii Fit

As commercial games like the aforementioned Wii Fit and Wii Sports Bowling became increasingly popular in the occupational therapy field, rehabilitation-focused Serious Games started

to emerge, with some of the earlier works actually using Nintendo Wii's accessories as rehabilitation tools with positive results [36].

A Serious Game can, thus, be summarized as a way to make rehabilitation sessions more engaging and less tiresome, as is often defined as a "videogame developed for a primary purpose other than entertainment" [37].

2.2.2 Developing a Serious Game

In order to make a Serious Game for rehabilitation purposes, some main criteria must be accomplished [38]. As such, the game must:

- Be made with a clear goal in mind;
- Be fine-tuned to accomodate entertainment and serious tasks;
- Promote onboarding and engagement;
- Manage important information;
- Be adapted for anyone;
- Make use of several channels, not only the visual one;

These points will be adressed in the following subchapters in further detail.

2.2.2.1 Goal Definition

To define the goal of a Serious Game is to answer the question "What should the user be training/learning while playing the game?". This goal is more subtle than the main objective of a gamified approach. Taking a previously mentioned example into account, Duolingo's main objective is clear: to teach anyone a foreign language of their choice. However, in order to keep the user committed in their learning process, it uses addictive game mechanics such as community boards, achievements and streaks [39]. This is a very different approach than the most common ones used in Serious Games. Taking the serious game Phylo DNA Puzzle [40] as another example, even though its presentation and entertainment value are that of a common leisure-oriented game, its objective is to make a community of non-scientists work together to solve the Multiple Sequence Alignment Problem. By presenting Phylo as a videogame, what seems to be a daunting task for geneticists, let alone common people, becomes a fun leisure activity. This game was made with a clear serious goal in mind, which allowed it to collect more than 250,000 solutions in its first seven months online [41]. As such, in order to make a serious game, the game developer must always keep the main objective in mind, while also creating a fun experience for anyone.

2.2.2.2 Entertainment and Serious Tasks

As briefly explored in the previous point, a serious game is an amalgamation of a utilitarian goal and leisure activities [38]. The game design must be a function of the main goal of the game. Thus, a tradeoff between player accessibility and scientific accuracy is required, which particularly applies to how the interaction between the game and the user is portrayed, how the graphics translate the goal of the game while remaining entertaining, and how the scoring system works.

2.2.2.3 Engagement

By regarding the user not as a patient but as a player, the need for an enticing experience becomes apparent: whereas most rehabilitation processes come from hard, tiresome and willpower driven sessions, the objective is for the user to actually want to engage in physical therapy as a dopamine-fueled gamer, eager to improve his or her high-score, to get to the next level, to get enough points to unlock a new playable character, or even to not break a well-earned multiple day streak. This turns a daunting task into a easily implemented good habit in the patient's life, which is particularly essential in the case of home therapy: if the user has unlimited access to the rehabilitation technology, the more engaging the experience, the better.

2.2.2.4 Information Management

Important information, in the particular case of physical therapy, is the amount of time the game is played per session, the number of sessions, and the player's progression through the sessions. Taking an even more specific example into account, when dealing with hand-force control, it's important to gather information about how the patient's force control improves, and, in some cases, how the patient's maximum hand compression force evolves over time. Without this data, the accomplishment, or lack thereof, of the game's goal cannot be tracked and, as such, the game loses credibility and practicality.

2.2.2.5 Universability

As it's essential to reach a broad audience and to maintain player interest [38], there are certain criteria regarding accessibility that should be kept in mind while designing a serious game. Simple controls help the entry-bar be lower, which is very useful when dealing with a non-gamer or technology illiterate audience, such as elderly people or small children. The game duration must also be kept to that of a casual mobile game: most casual games like Candy Crush Saga [42] and Flappy Bird (which the author actually removed from app stores on the grounds of it being "too addictive") [43] thrived in the 2010's mobile market for providing short, easy to pick up playing sessions. This worked because, in order to enter into a playing session, the user was not required to give up too much time to play the game, which paradoxically made these some of the games where players spent the most total time [44].

2.2.2.6 Sensory Feedback

The inclusion of multiple human senses in the rehabilitation process helps not only with player engagement, but also with preventing information overload. Instead of only resorting to visual feedback to convey the information necessary for the player, other senses like touch and sound can prove to be a great asset. Considering, again, the game Flappy Bird, the increment in the score value was translated not only into the visual interface, but also to the auditory interface, by including a triggered short sound whenever the score increased. This helps the player stay focused on the task at hand while also keeping track of the score without having to look at the score value while playing.

One of the main criticisms of the **SHaRe** system was the lack of tactile feedback: by allowing the system to be physically compressed in a significant way, the player has a stronger grasp of the amount of force he or she is using at any given moment, instead of just conveying this information through the **UI**, which should help the patient be focused on the task at hand.

By including these two fields into a Serious Game, engagement and task completion effectiveness can be greatly improved [38].

2.3 Synthesis

This chapter went over several of the available technologies for hand rehabilitation processes. The different types of Hand Rehabilitation Devices commercially available were reviewed, going over the advantages and shortcomings of each type of device, and how this influences the new prototype's development, with cases like the Power Glove showing that the new prototype must be easy for an end-user to set up and calibrate, while also being precise and relatively inexpensive. Afterwards, a study on the concepts of gamification and serious games was conducted, in order to provide a stronger understanding in how the new prototype's serious game must be developed to achieve the best possible results in patient engagement and improvement.

Chapter 3

SHaRe

SHaRe is a solution conceived to fill the gap in the realm of rehabilitation technologies. It harmonizes sensor-based technology, gamified applications, and rehabilitation mechanics to create a therapeutic environment that enhances patient engagement and facilitates effective therapy (figure 3.1). The concept of **SHaRe** originated from recognizing the limitations of existing solutions in response to the requirements of hand rehabilitation. At the time of its development in 2014, the system's initial model proved to be effective in its intended application. However, it had a crucial limitation as it was not suitable for a range of hand sizes due to its relatively large size.

Subsequently, a more compact version of the system, the blue model (as seen in figure 3.2), was developed, offering a more versatile and adaptable design that's adequate for various hand sizes. The design and functionalities of **SHaRe** align with the understanding that hand rehabilitation requires an approach that accommodates individual progress and ensures patients remain motivated through the process.

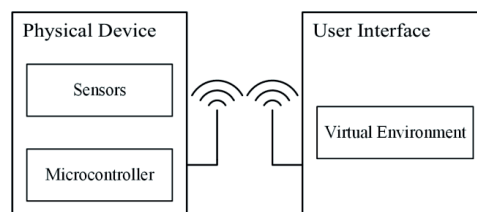


Figure 3.1: Diagram of the different components of the system [1]

3.1 Main Functionalities

SHaRe's design integrates a "Single Ended Beam" load cell instrumented with electrical strain gauges and an **IMU** into the device structure. The handling force applied during the rehabilitation exercise was possible to be recorded in the software database. However, an observed challenge was the force sensor reading different values depending on the position of the fingers on the device. This highlighted a scope for refining the design to ensure consistency in force readings, which will be explored in the following section.

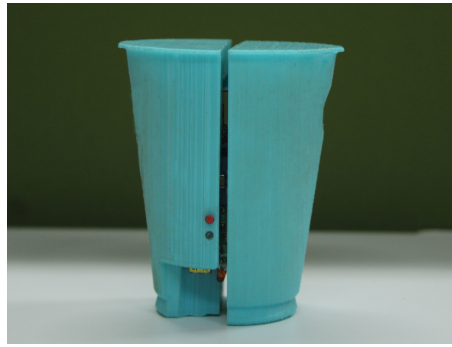


Figure 3.2: SHaRe device

3.1.1 Load Cell

SHaRe features a custom made single ended beam load cell, which, through its iterations, ranged from 0-70 N to 0-50 N [1, 45]. This aluminum load cell (figure 3.3 and figure 3.4) features two strain gauges for differential measurement of the deforming element (element 2 of the figure 3.3) as to correctly assess the applied force. Due to the load cell's architecture, the handling force is only measured when applied to element 4 (figure 3.3), which creates some hundreds of micro-strains in element 2 for a 5 kgf load. Element 1 is attached to the cup-shaped capsule, and its configuration can be seen in figure 3.5.

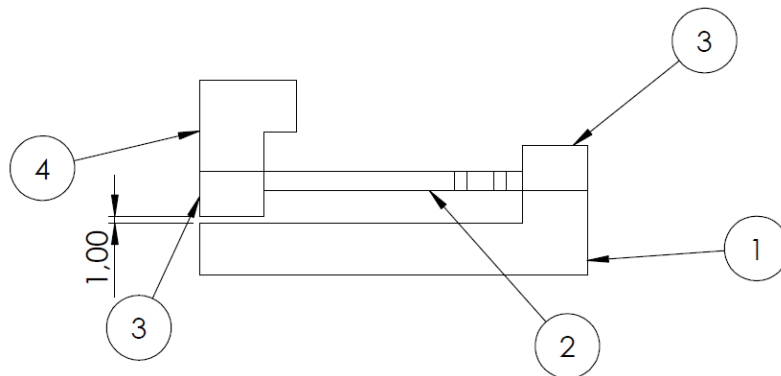


Figure 3.3: Load Cell's Components

- 1 = Base
- 2 = Deforming Element
- 3 = Clamping Element
- 4 = Force Application Element

This architecture, however, makes the measured force dependent on where SHaRe is gripped, which proved to be a problem in patients' hand force assessment. As such, when developing the new prototype's load cell, one major concern was to allow for the readings to be the same despite of how the user handles the cup.

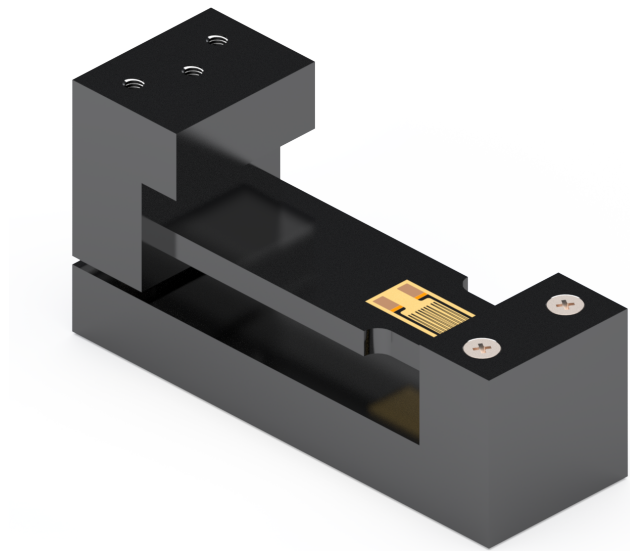


Figure 3.4: SHaRe's load cell

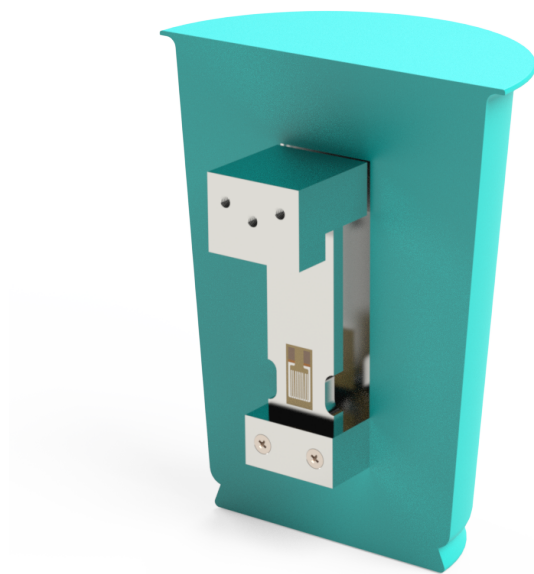


Figure 3.5: Load Cell's Orientation in the SHaRe Device

3.1.2 Inertial Measurement Unit

The **IMU** serves to capture the orientation of the device. The simultaneous operation of these components is fundamental to the system's ability to measure grip force and orientation concurrently, providing comprehensive data on hand movements and mechanics.

3.1.3 Serious Games

The applicability of SHaRe is further enhanced by its connection with various gamified applications. The system offers a range of games, each designed to challenge grip control and hand coordination. The games vary in their difficulty levels to cater to the evolving needs of the patients as they progress through their rehabilitation. The incorporation of game-based rehabilitation addresses the need for motivational tools in rehabilitation practices. These games were designed using the *Unity* game engine, and communication between the device and the game host (a Personal Computer) was assured through either the Bluetooth protocol or MiWi (a proprietary wireless communication protocol developed by Microchip Technology).

3.2 Clinical Feedback

From a clinical perspective, the impact of SHaRe has been promising. Patient feedback indicated a good acceptance rate of the system, with the majority expressing interest in using the system at home, if it ever became possible. The game-based approach fostered an environment that promoted patient motivation and facilitated their participation in rehabilitation exercises.

The therapists involved in patient rehabilitation using SHaRe noted an improved perception of grip force in patients after using the system over several sessions [45]. The potential for facilitating longer treatment periods without the continuous presence of a therapist was identified as a major advantage, promoting self-guided therapy and offering potential for remote training activities [1, 45].

3.3 Revisiting the SHaRe

Despite these positive outcomes and potential, the refinement phase of the SHaRe project was initiated, identifying four primary areas for improvement: lack of tactile feedback on deformation (due to its type of "isometric" force measurement), ergonomic issues, sensing and signal conditioning simplicity, and cost-effectiveness.

Addressing the issue with load cell readings became a priority to improve force readings and ergonomic handling. While developing a new load cell, as to allow the user to have a stronger grasp on the amount of force he or she is applying, a "milimetric displacement type" was targeted. This tactile feedback would however come with the downside of not being able to simulate different materials, a feature SHaRe was designed to have due to its isometric force measurement.

In addition, devising strategies to reduce manufacturing costs was deemed necessary for ensuring the widespread availability and accessibility of SHaRe. By rendering the device more cost-effective, SHaRe could potentially cater to a broader demographic of patients requiring hand rehabilitation, thus contributing to inclusive and accessible healthcare, and it could even be owned by the patients in order to use it from their own homes.

SHaRe is part of an innovative approach in the field of hand rehabilitation, bringing together sensor technology, mechanics, and gamified environments in an attempt to create a more patient-centered and engaging therapeutic platform. However, it is still a work in progress. The ongoing refinement of **SHaRe** to tackle identified limitations and to incorporate user feedback is a necessary step in its evolution. The intent is to improve both its efficacy and user experience. While **SHaRe** holds promise as a potentially impactful tool in the realm of hand rehabilitation therapies, it's important to improve on its shortcomings in order to provide a better user-experience overall.

Chapter 4

Selection and Development of a New Sensing System

The primary focus is to develop an alternative sensing system to the **SHaRe** system while being easily manufactured. The evaluation process undertaken in this chapter involves a careful assessment of various sensor options and load cell structures. By selecting an appropriate sensor and load cell structure, the aim is to overcome the limitations of the current design. This introduction provides an overview of the chapter's objective of overcoming the load cell's shortcomings and emphasizes the importance of sensor selection and load cell structure in achieving the desired outcomes.

4.1 Sensing Solutions

In order to evaluate grip strength, instead of developing a conventional strain gauge based load cell, which greatly increases the sensing process and its signal conditioning and therefore the cost of **SHaRe**, the new design is based on providing a load cell with an allowable deformation (for an applied force of 5 kgf, the same range as the **SHaRe**, a 5 mm displacement was considered optimal for tactile feedback). By having this range of displacement, the load cell makes it possible to use low-cost sensing solutions, such as Hall-Effect Sensors and Optic Sensors, while simultaneously providing the ability to transmit to the user a tactile sensation of the applied force.

4.1.1 Hall-Effect Sensors

Hall effect sensors were one of the main types of proximity sensors considered during the selection process for the new sensing solution. These sensors utilize the Hall effect, which is the generation of a voltage difference across two faces of a conductor when it is subjected to a magnetic field perpendicular to the conductor's current flow and parallel to the two faces (figure 4.1). In the context of load cell applications, Hall effect sensors offer the advantage of non-contact sensing, making them suitable for measuring forces without physical contact, by assessing the sensor's distance to a target that moves when subjected to a force [46].

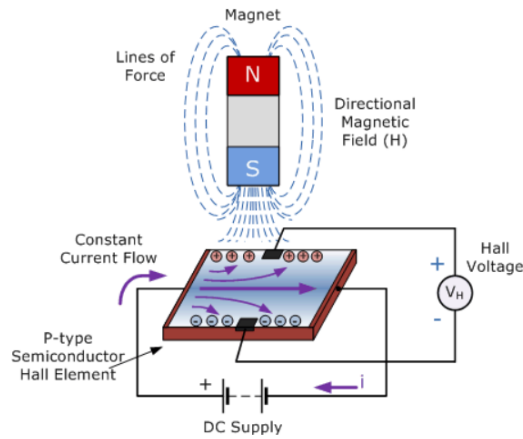


Figure 4.1: Hall Effect Sensor's working principle (from [46])

The output Hall voltage is given as:

$$V_h = R_h \left(\frac{I}{t} \times B \right) \quad (4.1)$$

Where:

V_h = Hall Voltage (V)

R_h = Hall Effect Co-efficient

I = Current Flow through the sensor (A)

t = sensor thickness (mm)

B = Magnetic Flux Density (T)

Since the magnetic flux density is a function of the distance to the magnet, the Hall Effect Sensor can be used to measure the distance between the sensor and the target (in this case a permanent magnet).

The sensor that was tested to apply in the new prototype was the AH49E, as it's an efficient (with a small form factor and low power consumption), almost linear, affordable and widely-used sensor. As we can see in figure 4.2, the sensor provides a linear response to the magnetic flux density from -1000 to 1000 Gauss, making it suitable for proximity detection.

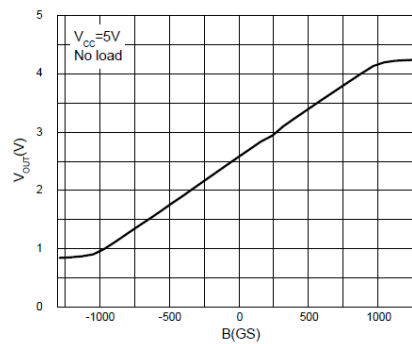


Figure 4.2: AH49E characteristic curve

4.1.2 Optic Sensors

The considered optic sensors in this selection process are the Vishay's TCRT5000.

The TCRT5000 is an infrared sensor that is widely used in applications like line-following robots, object counters and, most importantly, proximity sensors [47], and it consists of two main components: the emitter and the receiver. The emitter sends a beam of infrared light, which bounces off the target and is detected by the receiver. The intensity of the reflected light dictates the measured value in the receiver. The emitter and the receiver are housed in the same package, to guarantee their alignment.

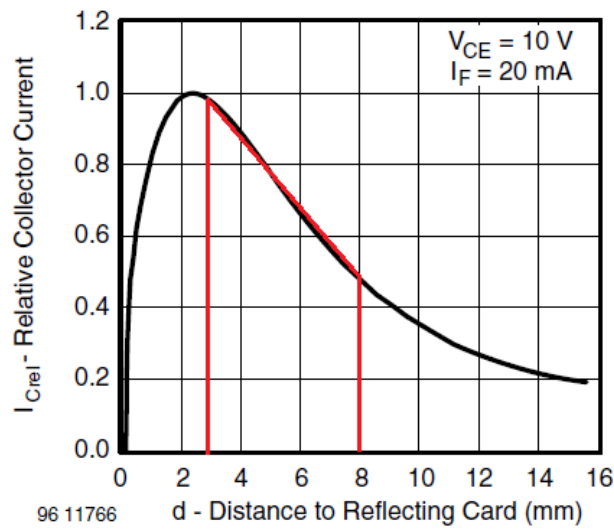


Figure 4.3: TCRT5000 characteristic curve (from [47])

As we can see in figure 4.3, the TCRT5000 presents an almost linear behaviour while detecting objects positioned 3 to 8mm from the sensor. As such, this 5 millimeter range can be used as a reference point for the load cell's displacement for 5 kgf, as this would allow for more accurate readings with the TCRT5000 while also providing a compression range that would feel natural and comfortable to the patient.

4.2 Sensor Implementation

In order to determine which sensor type to use on the load cell, the two sensors were tested in a laboratory environment, using a micrometric table to determine the distance to a target (figure 4.4). The TCRT5000's target was a reflective aluminum taped surface, and the Hall Effect Sensor's was an N35 neodymium magnet. Since the 5 millimeter range was to be used as a reference for the load cell's displacement, the sensors' applicability was tested for that range. Both sensors were powered using a **Rigol DP832A** power supply rated to 3.3V with a maximum allowed current of 0.040A. The measurements were made using a **Rigol DS1104** oscilloscope. A simple custom 3D printed part was developed to house both sensors at the same time, while providing support

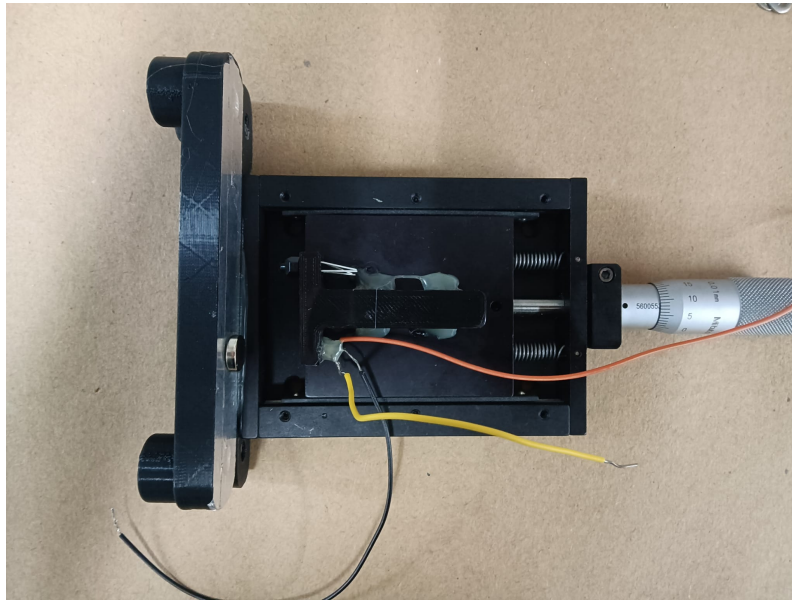


Figure 4.4: Micrometric table with sensors and target

and ensuring parallelism between the sensor and the target. The targets were fixed to the end of the micrometric table, in order to assure stability and measurement repeatability. As we can see in table 4.1, for a range of 5 millimeters, from 3 to 8 millimeters, both sensors have a very similar voltage range of about 0.5V, with the tcrt5000 presenting a slightly more linear behaviour than AH49E (with R^2 values of 0,985 and 0,969 respectively). However, the AH49E presented a higher level of noise in the measurements than the TCRT5000 (The AH49E had a constant noise with 100 mV of amplitude, while the TCRT5000's only had 20 mV). Furthermore, the hall effect sensor's measurements were noticeably influenced by outside interference from passing current. As such, the TCRT5000 was ultimately considered to be the most suitable sensing solution for this prototype.

Table 4.1: Measurements taken from the sensors

Distance to target (mm)	AH49E (V)	TCRT5000(V)
3	2.33	2.52
3.5	2.27	2,58
4	2.19	2.63
4.5	2.13	2.69
5	2.07	2.74
5.5	2.02	2.79
6	1.98	2.83
6.5	1.94	2.87
7	1.91	2.9
7.5	1.88	2.93
8	1.86	2.96

4.3 Load Cell Design

In order to accommodate for the 5 millimeter displacement (the optimal range for the tcr5000's linear behaviour), two different approaches to the load cell's design were considered: a **spring-based** design and a **single plastic component** design. Both design concepts are based on the linear elastic deformation of the load cell, dimensioned to deform 5 millimeters for an applied force of 5 kgf.

4.3.1 Spring-Based Design

This design was the first to be considered and developed for the load cell. The decision to opt for a spring-based design was influenced by the simplicity of the solution - By leveraging the inherent properties of springs, such as their linear behavior and predictable force-displacement relationship, the load cell can effectively translate applied forces into measurable values. The developed design can be seen in figure 4.5.

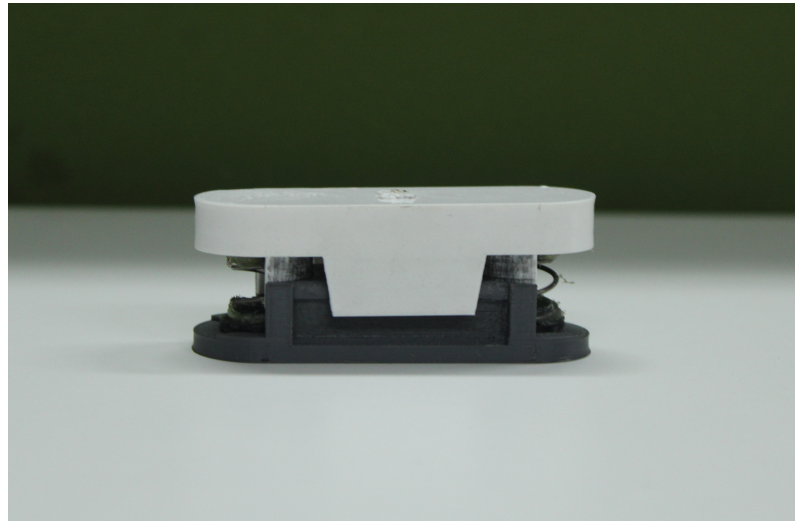


Figure 4.5: Spring-Based Load Cell

To ensure the load cell's performance aligned with the desired specifications, a thorough analysis and dimensioning process were conducted. Calculations were performed to determine the appropriate spring constants and dimensions required to achieve the desired 5 kgf maximum force capacity.

The helical coil springs were designed based on Shigley's Mechanical Engineering Design.

Shigley presents an equation for determining the spring's displacement based on its properties and the applied force:

$$y = \frac{8 \cdot F \cdot D^3 \cdot N_a}{d^4 G} \cdot \left(1 + \frac{1}{2C^2} \right) \quad (4.2)$$

Where:

F = Applied Force(N)

D = Spring Diameter(m)

N_a = Number of Active Coils

d = wire diameter (m)

G = Rigidity Modulus (Pa)

C = Spring Index

In turn, the Spring Index is given by:

$$C = \frac{D}{d} \quad (4.3)$$

The selected spring material was the ASTM A228 steel, more commonly known as Music Wire, as it's one of the most common and affordable steels for these kind of applications [48]. Its properties can be consulted in table 4.2.

Table 4.2: ASTM A228's mechanical properties

ASTM A228		
Property	Symbol	Value
Density	$\rho(g/cm^3)$	7.8
Elastic Modulus	$E(GPa)$	210
Poisson Coefficient	λ	0.313
Shear Modulus	$G(GPa)$	80

The required parameters are as follows in table 4.3.

Table 4.3: Fixed values in the spring design process

Property	Symbol	Value
Displacement	$y(mm)$	5
Force	$F(N)$	30
Spring Diameter	$D(mm)$	10
Free Length	$L_0(mm)$	12

The 30N force requirement was chosen because each of the two identical springs in the load cell would be subjected to a force of about 25N ($\approx 5/2kgf$), with an additional 5N to guarantee the load cell isn't fully compressed before reaching the 5kgf requirement.

After an iterative process, the final design was reached, and its parameters are in table 4.4.

By replacing these values, combined with the properties of the ASTM A228 steel to be used, in the displacement equation (equation 4.2), we get:

$$y = \frac{8 \cdot 30 \cdot (10 \times 10^{-3})^3 \cdot 2}{(1 \times 10^{-3})^4 \cdot (80 \times 10^9)} \cdot \left(1 + \frac{1}{2 \cdot 10^2}\right) = 5.025mm \quad (4.4)$$

Table 4.4: Final Spring Parameters

Parameter	Symbol	Value
Diameter	D (mm)	10
Wire Diameter	d(mm)	1
External Diameter	D + d (mm)	11
Spring Index	C	10
Force	F (N)	30
Free Length	L_0 (mm)	12
Solid Length	L_s (mm)	5
Pitch	p(mm)	4.5
Active Coils	N_a	2
End Coils	N_e	2

A load cell was created using the aforementioned springs, with a top piece and a bottom piece that snapped together (through a snap-fit joint) while allowing relative movement between the pieces (with repeatability guaranteed by the springs), as seen in figure 4.5.

The biggest downside of this type of design was that, by default, it would be impossible to remove friction between the pieces due to their relative movement, which created repeatability issues and wouldn't allow small force variations to be detected, as the pieces would not move. Friction could have been drastically reduced using a guidance system with self-lubricated parts. However, this would significantly increase the load cell's manufacturing cost, which went against this project's goal. As such, a new cell design concept had to be developed to eliminate relative movement between two pieces. This was achieved by creating a single plastic deformable component to convert the force to displacement.

4.3.2 Single Component Design

The single-component load cell was developed to mitigate the spring-based cell's biggest shortcoming: static friction.

This cell's design emerged from these principles:

- To be cheaper to produce, meaning it had to be a single plastic component;
- To operate in a way that it never reached the yield point, as to prevent plastic deformation;
- To have dimensions similar to SHaRe's load cell;
- To incorporate the optic sensors.

The plastic component design concept was based on *Gripwise's* patented load cell design.

Gripwise's load cell was created to measure grip strength regardless of how the device is handled. It consists of three main parts, as seen in figure 4.6.

Upper Part The upper part, shaped like a bracket, is rigid, and transfers the applied force to the extremities of the middle section.



Figure 4.6: Load Cell in Gripwise

Middle Part The middle part is an aluminum bar in *Gripwise* that deforms with the applied force and is fixed to the bottom section.

Bottom Part This part provides a pivoting point for the bar to guarantee its deformation with force.

Gripwise's load cell was developed using a strain gauge as it's main sensing solution in order to measure micro-displacements for relatively high compression forces. Since the new prototype's load cell is designed to measure low compression forces with a relatively high displacement, the design had to be rethought. With the goal of producing the simplest and cheaper Grip Training Device, the load cell was designed to be made out of a single plastic piece.

The new prototype's load cell was designed to be 3D printable, so it could be rapidly produced and tested, as many iterations were needed. Since the goal was to reduce the production costs, a decision was made to create the whole system in one single plastic component. The goal was, thus, to reach a new cell design in which the middle section deformed 5 mm for a force of 5 kgf without reaching a point of plastic deformation.

Since the load cell would be prototyped through 3D printing, the material chosen for the load cell's dimensions calculations was initially **ABS**, as it's the most likely material to be used in mass-produced injected parts, and it's 3D printable. However, due to difficulties in the cell's printing process in **ABS** (particularly derived from **ABS's** tendency to deform while printing), this material was, in a later stage of the project, replaced by **Polyethylene Terephthalate Glycol (PETG)**, which provided increased flexibility while also being easier to print.

The 3D model for the **ABS** model was created and studied in *SolidWorks 2022*. By selecting the part's material and submitting it to the desired compression force (in this case, 5 kgf),

SolidWorks provides a strong approximation of the piece's displacement and Von Mises stress distribution. This information can be used to evaluate the structural integrity and performance of the load cell design. To design a part without plastic deformation using the Von Mises Criterion, the maximum Von Mises stress must be below the yield strength of the material. The yield strength represents the stress level at which plastic deformation begins and is typically determined through material testing [48]. Since **ABS** plastics' yield strength typically ranges between 29.8 MPa and 48 MPa [49], the Von Mises equivalent stress should be kept below the lower end of this range to ensure a safe design. In other to reduce stress in the weakest parts of the piece (the junctions between the upper and middle sections, as seen in figure 4.8), the load cell had to be widened, thus exceeding the dimension requisites from the original **SHaRe** project (the original cup had a height of 95 mm, while the new load cell required a length of at least 110 mm). This required the cup's model to be modified to accomodate the load cell while also maintaining the comfort-oriented design of the original model. The printed design can be seen in figure 4.7.



Figure 4.7: One Bar Design

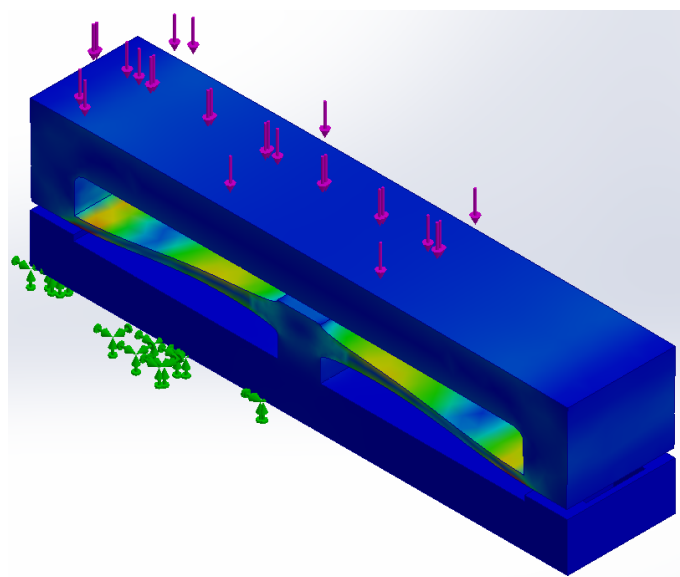


Figure 4.8: Stress Simulation in SolidWorks

Another problem that could occur in the load cell was fatigue. Since the load cell was developed to operate while subjected to forces of alternating intensity, the S-N curve of **ABS** had to be consulted in order to create a durable prototype [50]. As the true cyclic load is dependent on the patient's hand strength and type of developed exercise, a decision was made to consider the least favorable conditions to the load cell's durability. As such, the load was considered to alternate between 0 N and 50N. By calculating the stress amplitude (σ_a) (equation 4.5) and assuming the weakest R-Ratio (in this case, 0.1), it was estimated that the number of cycles the load cell would be able to perform was around 15000 cycles (as seen in figure 4.9, represented by the red lines).

$$\sigma_a = \sigma_{max} - \sigma_{min} = 23.3 - 0 = 23.3\text{MPa} \quad (4.5)$$

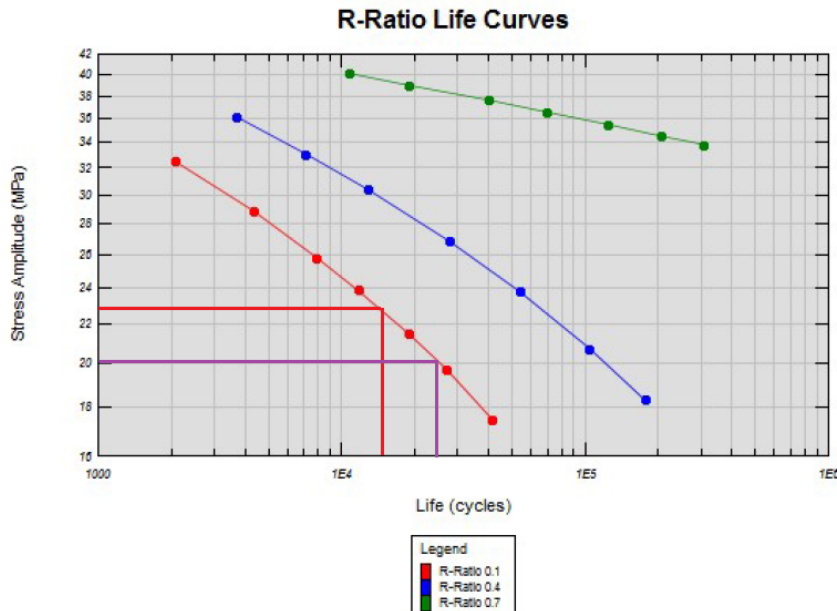


Figure 4.9: S-N curve for **ABS** (figure adapted from [50])

However, due to the nature of 3D printing and the consequent unevenness in tension distribution, most 3D printed load cells ended up breaking after less than 500 load cycles of use (test results can be seen in section 4.4). After multiple failed designs, these results led to another kind of design to drastically reduce stress (as shown in figure 4.10, in which the models were subjected to 5kgf of compression force using **ABS** as a material in the simulation for comparison): instead of having a single flexing bar in which all the tensions were concentrated, the design was adapted to accommodate two flexing bars. Due to the fact that the **PCB** (discussed in the following chapter) had already been produced at this stage of development, and the distance between the optic sensors was fixed by the **PCB**, the new design had to adhere to the single bar design's determined length.

What this meant in this production phase was that, in order to use the same **PCB**, the new cell was lengthier than necessary (as tensions in critical parts were greatly reduced).

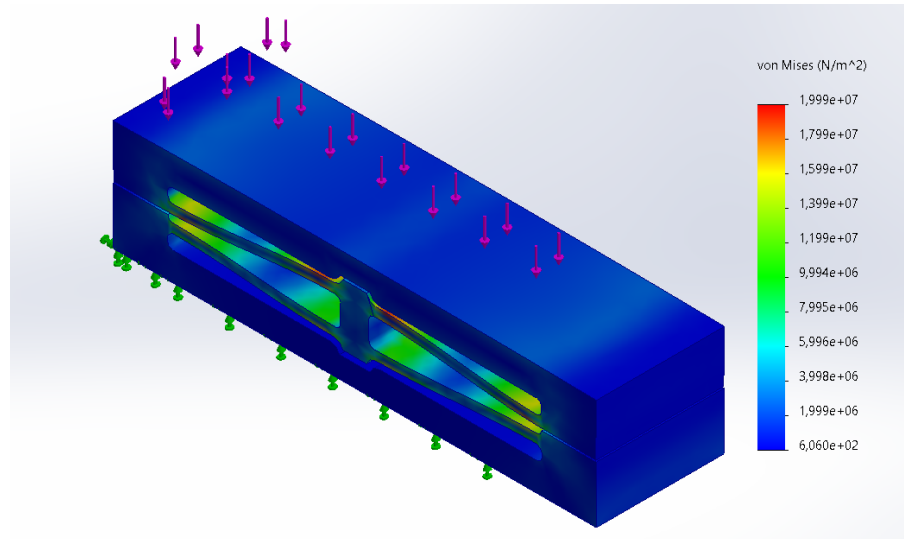


Figure 4.10: Von Mises Stress for 5kgf with a 5mm displacement

As seen in figure 4.10, the maximum stress in this configuration was reduced to 20 MPa, which should lead to an increase in the number of work cycles from 15000 cycles to 25000 (as seen in figure 4.9, represented by the purple lines)

As load cells printed in **ABS** filament consistently had warping issues, making them difficult to produce, the decision was made to start using **PETG** filament. This material replacement was also caused due to **PETG** being widely considered to be more flexible than **ABS** [51, 52]. However, this led to difficulties in the prediction of the design's behaviour when submitted to compression force, as there's a severe lack of documentation regarding **PETG**'s mechanical properties, which can also vary from supplier to supplier. As such, the design process was more iterative than based on calculations, and multiple cells were produced until a final design was reached. This design (figure 4.11) was reached by iteratively altering the thickness of the middle section's bars until a 5mm displacement was reached for a 5kgf compression force. Due to the nature of this process, stress at critical points isn't known, as the printed material's mechanical properties are unknown. However, it was considered to be safe to assume that stress was greatly reduced when compared to the one bar design.

A final remark important in this stage is the fact that the choice for white filament (be it **ABS** or **PETG**) was due to the finding that the used optic sensors, TCRT5000, had the widest current range without saturating when the reflecting card (figure 4.3) or target had higher reflectivity (a mirror target would saturate the signal). As to obtain the widest possible range from the sensors, which would in turn increase the device's resolution, the target was thus determined to be white. By printing the whole plastic part in white filament, a simple solution was, as such, reached in order to optimize the sensing system.

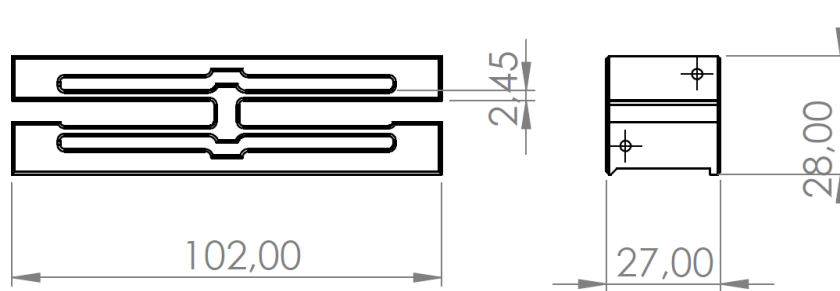


Figure 4.11: Final Cell Design

This design's 3D print in PETG can be seen in figure 4.12 alongside the optic sensor integration in the load cell.

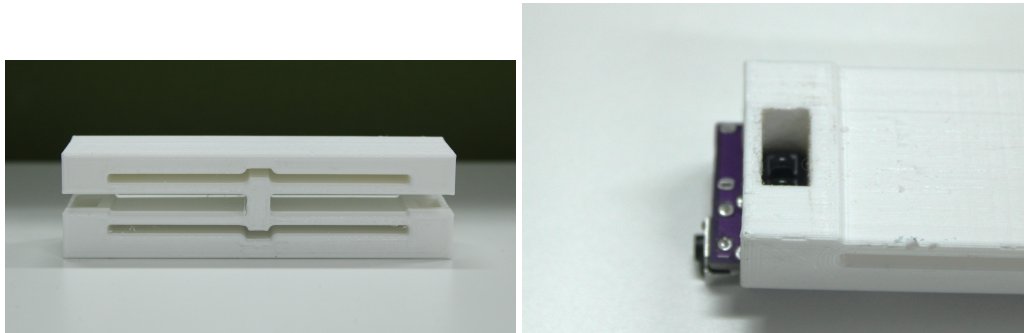


Figure 4.12: Final Load Cell (left) and sensor placement in the load cell (right)

4.4 Load Cell Testing

In order to test the developed load cell and compare it to the other solutions considered in this chapter, two testing machines from Gripwise Tech, Lda. were utilized.

4.4.1 Compression Force Measurements

These tests were conducted using the GripTester, a custom made machine. A strain gauge based load cell located at the base of the testing system measures the force applied by a screw that, by turning, compresses the part or device (in the case of the Gripwise device) and displaying the results on a LCD screen (figure 4.13).

This testing system allowed the multiple produced cells to be accurately tested in regards to their maximum compression force. This section will present the main three cells results before any working cycle. The three cells to be compared are:

- The one bar ABS design (referred to in this chapter as cell 1);
- The two bar ABS design (referred as cell 2);

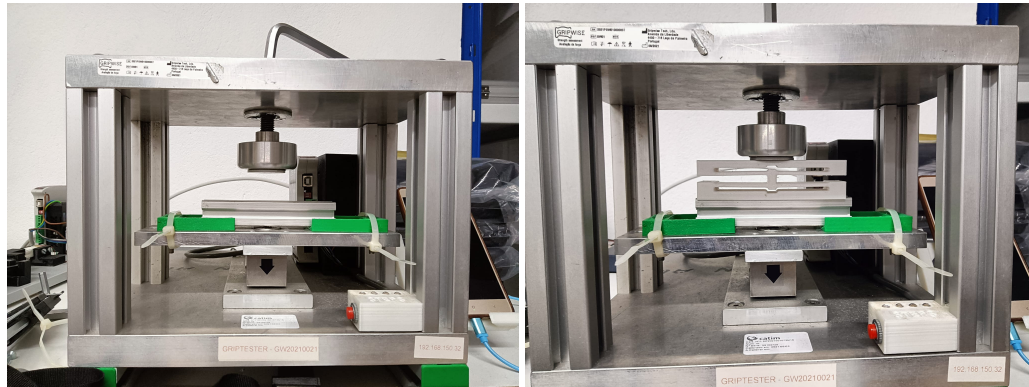


Figure 4.13: GripTester with and without the tested load cell (right and left, respectively)

- The two bar **PETG** design (cell 3), which, due to the lack of information regarding the material's mechanical properties, made it impossible to predict the number of working cycles.

Both cell 1 and cell 2 were fine-tuned using Solidworks simulation to have a 5 mm displacement for a 5kgf compression force, while cell 3 was obtained through an iterative process. For the different cells the force measurements were performed by turning the GripTester screw until achieving the 5 mm displacement. These results can be seen in table 4.5.

Table 4.5: Force values at 5mm displacement for Load cells 1, 2 and 3, before submitting them to compression tests

Cell	Force (kgf)
1	6.11
2	5.46
3	5.15

4.4.2 Fatigue Life Testing

To know the fatigue life of a load cell, which indicates the number of times a rated capacity can be loaded, a testing machine was adapted to subject the parts to cyclical force. This machine's main components are:

- An ESP8266 development board that implements the motor behaviour based on the load cell readings;
- A DC brushed motor that applies pressure on the load cell in cycles;
- A strain-gauge based load cell that limits the pressure to 5kgf.

Each cell was tested regarding the number of cycles it was able to perform before breaking. Using the GripTester, some measurements of each cell's compression force were made in-between cycles.

Table 4.6: Fatigue Life of Each Load Cell with compression force measurements in-between cycles (in kgf)

cell	Number of Cycles								
	0	300	1000	5000	10000	15000	20000	50000	60000
1	6.11	failure							
2	5.46	5.46	5.46	4.5	4.37	failure			
3	5.15	5.15	5.15	5.15	5.15	5.15	5.14	5.06	failure

To calculate the duration of the load cell, it's possible to estimate that, during a therapy session, the prototype will be fully compressed, in average, 25 times per minute. With this consideration, it's reasonable to assume the load cell will not be at risk of failure for the first 2400 minutes or 40 hours of continuous use. It should also be mentioned that these tests were conducted in 3D printed cells, and, as such, these results wouldn't translate to load cells manufactured through injection molding. In fact, it's safe to assume that injection molded load cells in **PETG** or **Polyethylene terephthalate (PET)** would perform a significantly greater number of cycles than this prototype, as can be seen from the discrepancy in expected number of cycles (as previously seen in figure 4.9) and performed cycles before failure in the **ABS** load cells.

4.5 Synthesis

After testing two main types of sensors and two main types of cell designs, a final plastic, single part load cell was developed by adapting the *Gripwise's* load cell design to accomodate two optic sensors and to prevent plastic deformation. The chosen material for this new load cell was initially **ABS**, as it could be cheaply mass produced and prototyped through 3D printing, but ultimately this material was replaced by the more flexible and easy to print **PETG**, which allowed multiple iterations to be made before reaching a repeatable and durable load cell.

Chapter 5

Implementation of a Microcontroller System with Bluetooth Connectivity

The inclusion of an electronic system is a major requirement in a project like this: as to make the prototype autonomous, an integrated PCB had to be developed to implement the sensors, signal conditioners, Analog-to-Digital Converter (ADC) module, a processor, a battery system and communication system.

The electronics in this new prototype had to attend to the following minimum requirements:

- To acquire the data from the optic sensors and process it;
- To send the data through Bluetooth;
- To be powered by a rechargeable battery.

In order to avoid the need to implement a Bluetooth module, a processor, and an ADC, while still being able to program the prototype using the Arduino IDE, an Espressif ESP32-WROOM-32 module was considered to be a suitable choice for the electronic implementation, saving time in the programming phase, which was not the focus of this work. The ESP32's function is summarized in figure 5.1.

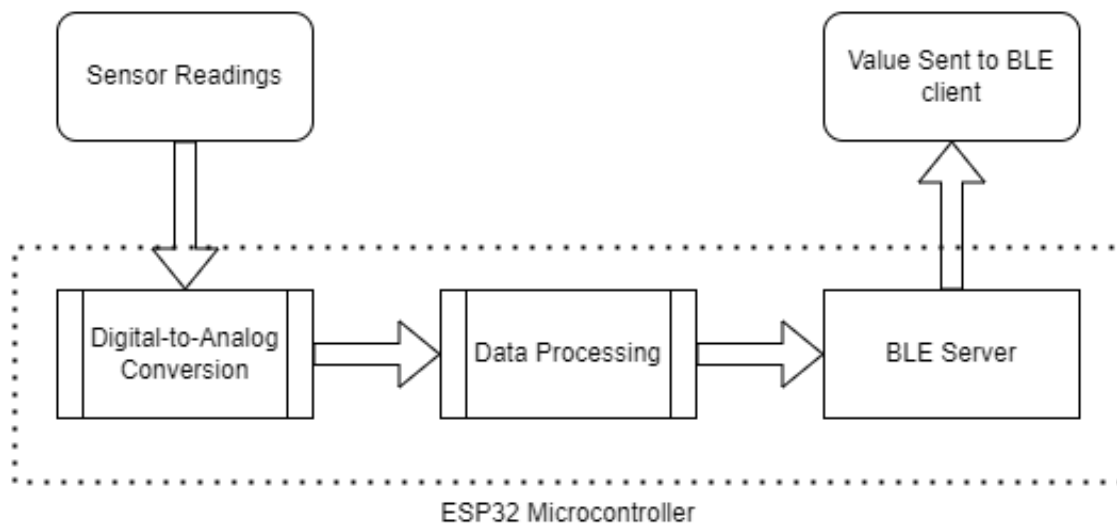


Figure 5.1: Diagram of the Input/Output Process

5.1 ESP32 Circuit Board Design

The ESP32 is a 32-bit microcontroller designed by Espressif. As a microcontroller, it consists of a **Central Processing Unit (CPU)**, memory, and various input/output (I/O) peripherals integrated onto a single chip. The ESP32 is a highly versatile microcontroller that is widely used in various applications, including **IoT** projects.

It's key features encompass Wi-Fi and **Bluetooth Low Energy (BLE)** connectivity, extensive library and community support, the ability to program using the Arduino **IDE**, and ample **General Purpose Input/Output (GPIO)** pins, including fifteen 12-bit **ADC** pins. Regarding the particular module used, it's main characteristics can be found in table 5.1.



Figure 5.2: The ESP32 Module

In order to design the circuit, certain components had to be implemented, namely:

- A battery, to allow the device to be powered on without an external power source;

Table 5.1: Characteristics of the ESP32-WROOM-32

ESP32-WROOM-32	
Characteristic	Description
CPU	Dual-core 32-bit Xtensa LX6 microprocessor
Memory	Integrated RAM (520KB) and flash memory (4MB)
Connectivity	Built-in Wi-Fi (802.11 b/g/n) and Bluetooth 4.2/ BLE
GPIO	Abundant GPIO pins for interfacing with external devices
ADC Pins	15 ADC pins (ESP32-WROOM-32D)
Digital-only Pins	18 digital-only pins (ESP32-WROOM-32D)
I/O Peripherals	SPI, I2C, UART, ADC, DAC, and more
Power Management	Sleep modes for power optimization
Development	Compatible with Arduino IDE , ESP-IDF, and Micropython
Library and Support	Extensive community support and available libraries

- A battery charger, to manage and charge the battery efficiently;
- A USB charging port, to allow for easy charging of the device;
- A voltage regulator, to guarantee a steady 3.3V power supply;
- A RGB **Light Emmiting Diode (LED)** to provide visual feedback to the user;
- A power button, to turn the device on and off and to allow the user to tare the device.

The circuit was designed in EAGLE PCB and, after selecting the required components and incorporating the auxiliary electronic components to drive the circuit (such as resistors, diodes and capacitors). The specific choices for the aforementioned electronics can be found in table 5.2.

Table 5.2: Main Circuit Components

Battery	3.7V 500mAh Li-Po battery
Battery Charger	MAX1555
USB Charging Port	USB female Type C connector
Voltage Regulator	AP2112K-3.3

After reaching a final schematic, the custom **PCB** was created. This circuit board was designed to be attached directly to the load cell, and, as such, it was developed to fit in the dimensions of the load cell while guaranteeing the two optic sensors had the right distance between them and the USB Type-C connector and the power button were easily reachable, which proved to be a lengthy process to perform. Once the final board design was ready, the Gerber files were sent to JLC PCB to manufacture the circuit board, which was then assembled (figure 5.3).

5.2 Firmware implementation

As mentioned in previous chapters, one of the more convenient aspects of the ESP32 microcontroller is the ability to develop it's firmware using the Arduino **IDE**, which is a popular and widely

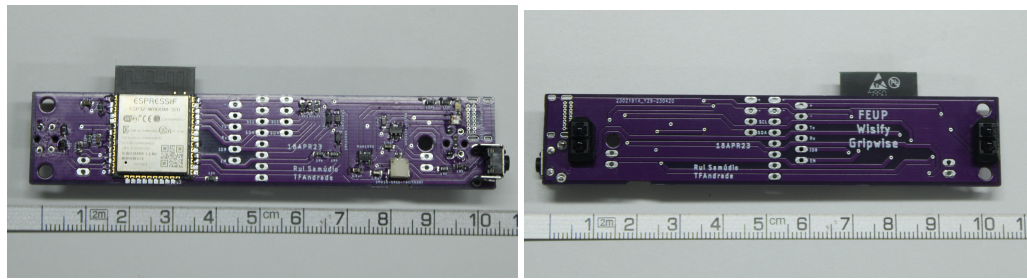


Figure 5.3: Custom made PCB

used **IDE** for microcontrollers and prototyping purposes, due to its user-friendly interface, extensive community support, and a vast library of pre-existing code and examples that simplify the development process for beginners and experienced developers alike. The implemented firmware sought to cover these four main systems:

- Data Acquisition System;
- Bluetooth Communication;
- Tare function;
- Basic Functionalities.

Each system is going to be explained in the following subchapters.

5.2.1 Basic Functionalities

This system covers the basic logic of the device's behavior and functionality. It includes the following aspects:

- **Pin Configuration:** The necessary pin modes are set for various input and output pins used in the system;
- **LED Control:** The firmware initializes the Adafruit_NeoPixel library to control an **LED** connected to pin 32. The **LED**'s color indicates the device's operational state, and changes depending on the battery's level (green indicates a high battery level, orange suggests the battery is working at half capacity, and red tells the user the device has a low battery);
- **Button handling:** The firmware continuously checks the button state and listens for button events such as press and hold. Depending on the button actions, corresponding actions are performed, such as powering off the device or triggering the tare function;
- **Device Sound Cues:** A buzzer connected to pin 26 plays three different melodies depending on the cup's state: a melody for turning on the cup, a melody for powering off the prototype, and a melody to indicate the tare function has been completed.

5.2.1.1 Data Acquisition System

This system focuses on acquiring data from the optical sensors and performing calculations for measurement purposes. The key features include:

- **Sensor readings:** The firmware reads analog sensor values from two optical sensors connected to the ESP32 microcontroller.
- **Data storage:** The measured values are stored in arrays for further processing.
- **Average calculation:** The firmware calculates the average values from the sensor readings.
- **Measurement result:** The final measurement result is obtained by subtracting the offset values from the average values.

The data acquisition system in the firmware utilizes a moving average filter for signal processing, which is a common technique used to reduce noise and fluctuations in a signal by smoothing out the variations over a specified window size. The filter takes the last n inputs (with n being the window size) into account and computes their average value, which is then used as the filtered output. By considering a certain number of past samples, the moving average filter provides a smoothed representation of the input signal. The window size determines the number of samples included in the average calculation, thereby influencing the level of smoothing applied to the signal. A larger window size results in a smoother output but may introduce more latency, while a smaller window size provides a more responsive output but with less smoothing.

In this implementation, the firmware reads analog sensor values from two optical sensors connected to the ESP32 microcontroller. These sensor readings represent the compression of the load cell (the compression of the load cell leads to a smaller gap between the target and the optic sensor), which are then processed using the moving average.

To address this trade-off between responsiveness and noise reduction, the firmware employs an adaptive window size. The adaptive nature of the window size allows it to dynamically adjust based on the behavior of the target and the sensor readings. When the target speed increases or there are small signal changes, the window size reduces to provide a more responsive output. On the other hand, when the target speed decreases or there are larger signal changes, the window size increases to maintain stability and reduce noise impact.

The window size is adapted by calculating the difference between the current measurement and the measurement from the last loop. As the absolute difference increases, the size of the average array decreases, which allows for lower smoothing when the signal is varying rapidly.

By using an adaptive moving average filter, the firmware optimizes the signal processing to capture both the fine-grained changes in target position and the overall trend of the compression data. This adaptive approach enhances the accuracy and reliability of the measurements obtained from the optical sensors, enabling effective monitoring and control of the load cell system.

After processing the signal from each sensor measurement, the value obtained from the tare function (explored in the following section) is subtracted from the output of the filter to offset the

values. Lastly, a final variable (Measure), which is the one to be sent via BLE, is calculated from the data of each sensor.

5.2.2 Tare Function

To avoid measurement errors due to drifting, it is necessary to zero the device in order to set a reference point. This implementation is called tare function. By establishing a reference point, the tare function ensures that subsequent measurements are relative to this reference, providing accurate and reliable data.

The tare functionality is triggered by a short button press, which activates the zeroing process. When the tare button is pressed, the firmware sets a tare flag to true and records the current timestamp.

After 4 seconds, the firmware performs the tare operation to adjust the average values obtained from the optical sensors. The tare operation involves subtracting the current average values from the stored reference values, effectively nullifying any initial values and offsets for each sensor, which establishes a new reference point for subsequent measurements.

Once the tare operation is completed, the firmware resets the tare flag to false, indicating that the system is ready to provide accurate measurements relative to the newly established reference point.

This functionality ensures that the optical sensor readings are zeroed and accurate by removing any undesired initial values or offsets. This process enhances the reliability and precision of the data acquisition system, enabling accurate measurements.

By incorporating the tare function, users can easily zero the system to eliminate any systematic errors and ensure that subsequent measurements reflect only the desired changes or variations in the optical sensor readings.

5.2.3 Bluetooth Communication

As previously mentioned, one of the major advantages of utilizing the ESP32 is its ability to establish wireless communication to smartphones and tablets through Bluetooth Low Energy Communication, which is a variant of traditional Bluetooth designed for low-power and low-data-rate applications. It operates in the same frequency range as Classic Bluetooth but consumes less power and offers faster connection setup times. BLE is optimized for intermittent data transmission and is suitable for devices that require long battery life and have limited processing capabilities, which is the case of the developed prototype. Bluetooth communication relies on a client-server architecture, where the ESP32 device acts as a Bluetooth server, and the external device acts as a Bluetooth client.

The Bluetooth communication process involves the following key concepts:

1. Bluetooth Server The ESP32 device functions as a Bluetooth server. As a server, it provides services and characteristics that define its functionality. Services represent specific functionalities offered by the firmware, while characteristics define specific data attributes within those services. For example, the firmware may have a service called "Measurement Service" and a characteristic called "Measurement Data" to provide measurement data to the Bluetooth client.

2. Bluetooth Client: The external device, such as a smartphone or tablet, functions as a Bluetooth client. The client scans for available Bluetooth devices and discovers the services and characteristics provided by the ESP32 firmware. It then establishes a connection with the ESP32 device to interact with its functionality.

3. Advertisement: The ESP32 firmware configures the device to advertise its availability as a Bluetooth device. This advertisement includes information about the services provided by the firmware, allowing nearby Bluetooth devices to discover and connect to it. The advertisement typically includes the device name, service UUIDs, and other relevant information.

4. Connection: The Bluetooth client scans for available Bluetooth devices and detects the advertisement from the ESP32 firmware. Upon finding the ESP32 device, the client initiates a connection request to establish a communication link. The ESP32 firmware can accept or reject the connection request based on its configuration.

5. Service and Characteristic Interaction: Once the connection is established, the Bluetooth client can interact with the services and characteristics provided by the ESP32 firmware. The client can read from, write to, or subscribe to notifications or indications from the characteristics. In this particular case, the client reads the measurement data (the Measure variable) from the data acquisition system.

By implementing Bluetooth communication, the ESP32 firmware enables external devices to connect and interact with the device's functionality, which will allow the data to be used to control a game and gather patient improvement statistics. Through services and characteristics, the firmware provides a means for exchanging data and commands between the device and the Bluetooth client.

The Bluetooth communication functionality in the firmware is made possible by utilizing the ESP32's built-in Bluetooth capabilities and the associated **BLE** libraries. These libraries, such as **BLEDevice**, **BLEServer**, **BLEUtils**, and **BLE2902**, provide the necessary functionality to configure the ESP32 as a Bluetooth server, handle the service and characteristic interactions, and manage the data exchange between the ESP32 and the Bluetooth client.

5.3 Sensing System Characteristic Curve

With the electronics fitted into the load cell, and the ESP32 programmed, the new sensing solution's characteristic curve was approximated. In order to produce stable output, the signal firmware-based processing resulted in a range of 0-250 bits for a 0-5 kgf load. The system's resolution is calculated in equation 5.1.

$$Resolution = \frac{loadcell_{range}}{out put_{range}} = \frac{5000gf}{250} = 20gf \quad (5.1)$$

The system was subjected to varying forces to determine its characteristic curve, which can be seen in figure 5.4.

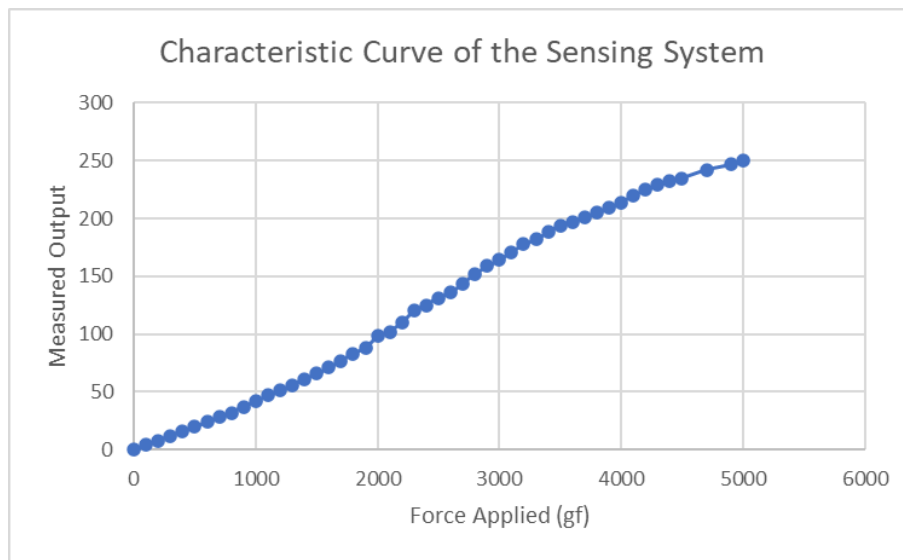


Figure 5.4: Characteristic Curve of the Sensing Solution

As seen in figure 5.4, the sensing solution's approximated curve presents an almost linear behaviour, with a R^2 value of 0.993 and a Standard Deviation of 6.70. As such, no calibration was performed on the device, and the Serious Game explored in chapter 6 was controlled assuming a linear response.

5.4 Synthesis

The electronic system for the prototype was developed using an ESP32 microprocessor, which allowed the development of the firmware using the Arduino **IDE**. The firmware manages the device's basic logic, while processing the acquired data and providing Bluetooth communication and a tare function. The **PCB** created for the prototype was designed in Eagle PCB and assembled on site. The **PCB**'s integration in the load cell can be seen in figure 5.5.

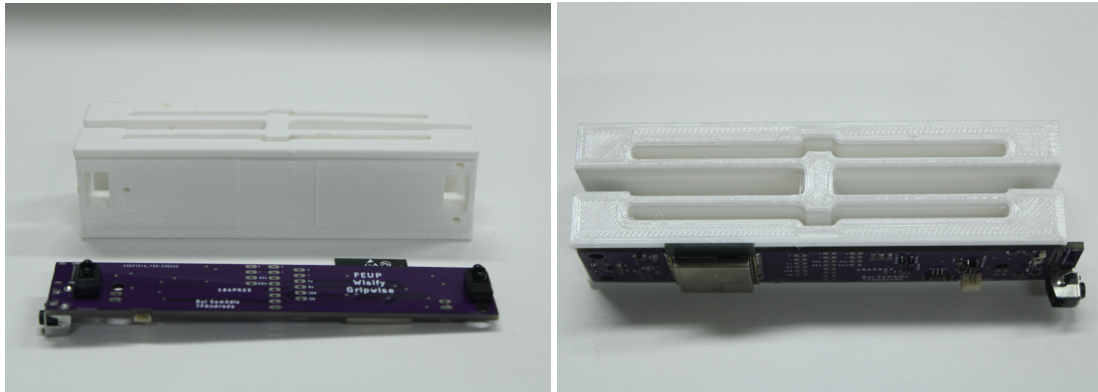


Figure 5.5: PCB integration in the Load Cell

Chapter 6

User Interface Incorporation

The main function of the SHaRe system is to provide a gamified approach to hand rehabilitation (chapter 3). As such, an engaging and efficient game had to be created, to provide a stimulating environment for the user. The Unity-based mobile game *Flappy Bird*, a traditional casual mobile game in which a player controls the bird character to pass through pipes, has already been successfully used to aid in hand rehabilitation [8], providing a blueprint for the custom user interface developed for the new prototype.

As previously elaborated on section 2.2.2, the development of a Serious Game should adhere to some game development rules. A Serious Game should:

- Be made with a clear goal in mind;
- Be fine-tuned to accommodate entertainment and serious tasks;
- Promote onboarding and engagement;
- Manage important information;
- Be adapted for anyone;
- Make use of several channels, not only the visual one;

This new Unity-based game developed for Android systems is meant to offer visual feedback of the load cell readings while also encouraging the patient to improve in the game and, as such, in their rehabilitation process. Thus, some key features had to be implemented:

- Engaging gameplay;
- Bluetooth Communication with the ESP32;
- Visual feedback of the load cell's compression.

The stages of development are explained in the following sections.

6.1 Goal Definition and Universality

The main goal of this Serious Game is to provide a simple and engaging way for patients to use the new prototype to train hand grip control. As some patients may struggle to maintain isometric grip force while others have problems with timed impulses, the game was separated into 3 small minigames:

- **Rocket:** for force and impulse control;
- **Rocket Impulse:** for impulse control;
- **Force Control:** for force control;

These minigames helped ensure that most patients' needs would be somehow addressed. However, as to increase universality and to make the minigames accessible to anyone, a sensitivity setting and difficulty levels were included to help patients with less hand grip strength engage with the game.

6.2 Entertainment and Engagement

As previously mentioned both in the beginning of this chapter and in section 2.2, the game *Flappy Bird* was chosen as a blueprint for its accessibility and addictiveness [43]. Despite the main goal of the serious game being to provide an interface for hand grip training, the inclusion of engaging mechanics is a way to promote patient compliance with the rehabilitation process. Thus, the game includes 3 main features to provide an engaging therapy interface:

- Custom-made 2D sprites;
- Score System;
- Leader Boards.

6.3 Information Management

As to easily manage different patients' information, a simple username system was implemented, which allows therapists to easily separate each patient's data. A csv file is constantly collecting each patient's data, regarding obtained score, force values throughout the session, sensitivity level and difficulty level used.

6.4 Multi-Sensory Feedback

The combination of the visual interface with the load cell's 5mm range of displacement allows for a sensory feedback that encompasses not only visualization but also tactile feeling.

6.5 Gameplay

The main game incorporates a **UI** with access to 7 buttons, after logging in with the user's username (figure 6.1):

- **Rocket**: initiates the minigame Rocket;
- **Rocket Impulse**: initiates the minigame Rocket Impulse;
- **Force Control**: initiates the minigame Force Control;
- **Google Form**: allows the user to fill a Google Form on the user's experience;
- **Highscore**: shows each game's best scores to date;
- **Settings**: allows for changes in the prototype's sensitivity and games' difficulty;
- **Change User**: takes the user back to the Login Screen.

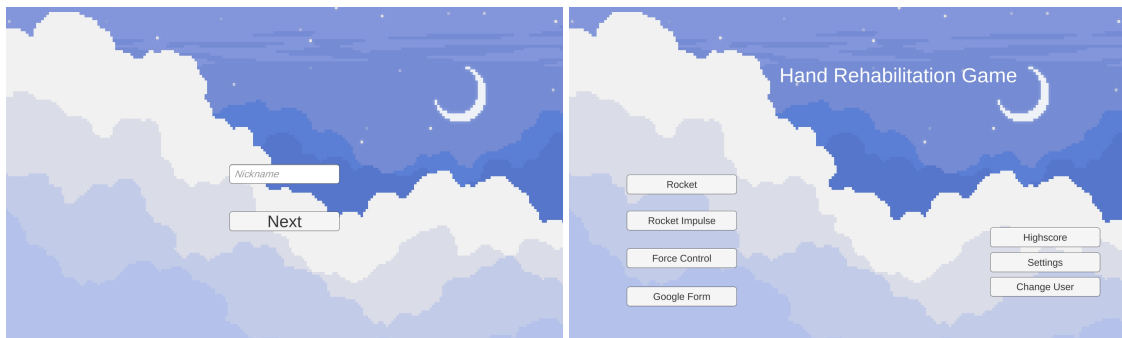


Figure 6.1: Login Screen (Left) and Main Screen (Right)

The following sections will go over each minigame, as well as the **BLE** communication established.

6.5.1 Rocket

As to make the process more engaging for the user, some basic game design features were implemented, using the game *Flappy Bird* as a starting point:

- The objective is to survive as long as possible by avoiding pipes or columns;
- Players earn points for successfully passing through each set of pipes;
- A highscore system is present, encouraging the player to improve.

In this minigame (seen in figure 6.2), the biggest difference is the way the player controls the character. While in *Flappy Bird*, the bird character is controlled by tapping the screen, the new game utilizes the prototype's ability to send the load cell's measure data to continuously control

the player character (a rocket) up and down. As such, this minigame encourages not only impulse timing control, but also grip force control. In order to progress through the pipes, the player has to continuously be focused on the applied force as well as the timing of that force. The Game Over screen (right side of figure 6.2) displays the user's username ("test" on figure 6.2), the obtained score and the highest score the user ever achieved. The "Try Again" button allows the user to replay the minigame, while the "Main Menu" button takes the user back to the main menu.

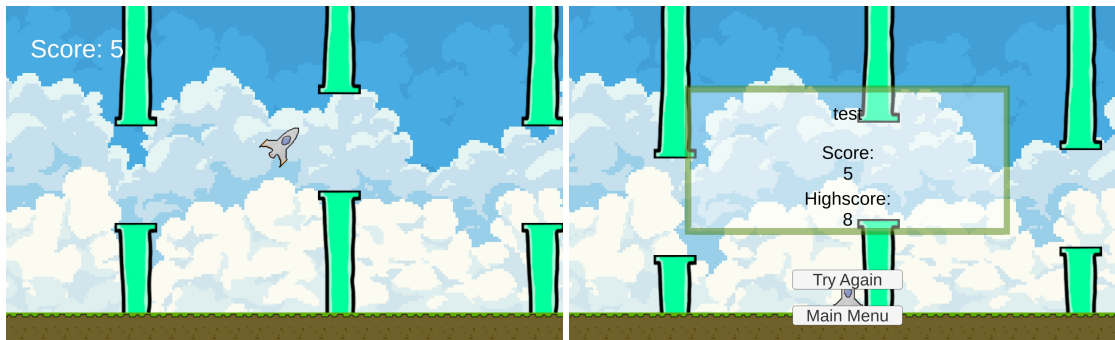


Figure 6.2: "Rocket" gameplay (left) and Game Over Screen (right)

6.5.2 Rocket Impulse

This minigame was developed to provide an easier game for the patients, while maintaining the features from the minigame "Rocket". As the continuous control of hand force and impulse timings may be a daunting task for some patients, this minigame focuses only on force impulses: Once the player compresses the cup beyond a pre-determined threshold, the rocket is propelled up. This game is the most similar to *Flappy Bird*, as the cup's compression behaves as a screen tap would in the mobile game. The visual side of "Rocket Impulse" is identical to "Rocket", with the only difference between the two being, as such, how the player character (the rocket ship) is controlled.

6.5.3 Force Control

This third minigame was created to allow users to only train handling force by removing the impulse timing aspect of the previous minigames. This minigame's player character is a pink bar that the user controls by compressing the cup. By positioning the pink bar between two limits (a green bar as the upper limit and a red bar as the bottom limit), a timer will start counting down (figure 6.3). In each stage, when the timer reaches zero, the player gets a point, the limits' position changes randomly and the distance between the limits decreases. The player loses if he or she fails to position the bar between the limits for more than a given number of seconds (the timers' value and the distance between the bars are dependent on the game's difficulty setting).

6.5.4 BLE Communication

In order to establish a wireless communication between the Unity-based game and the ESP32, an external asset had to be implemented: The Bluetooth LE for iOS, tvOS and Android, from

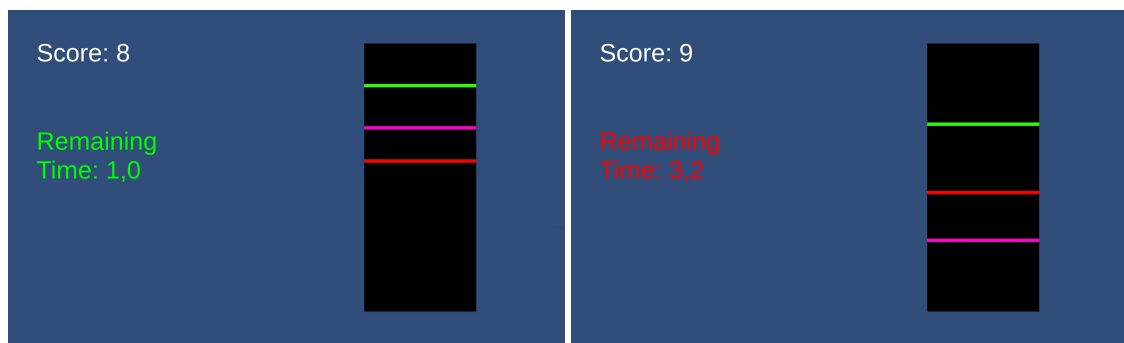


Figure 6.3: Pink bar between the limits (left) and outside the limits (right)

Shatalmic, Inc. This asset included templates for Bluetooth communication with the Arduino HM10 Bluetooth module, which was adapted to use with the ESP32's existing firmware. By including the new script as a game object in the game, it became possible to establish communication between the ESP32 and the Android game, thus creating a user interface to gather data from the prototype.

6.6 Synthesis

A Unity-based serious game was created to provide a visual and engaging interface for the hand rehabilitation process with the new prototype. The cup serves as a controller for three minigames with different goals. Some features, such as difficulty and sensitivity levels, as well as Leader Boards and High Scores, were added to create a more accessible and fun experience to the rehabilitation process.

Chapter 7

Assembly, Validation Tests and Results

7.1 Prototype Assembly

With the load cell, the **PCB** and the Serious Game developed, the prototype was assembled. Three different parts were modeled and 3D printed in **Polylactic Acid (PLA)** to create the final cup design.

7.1.1 Board Protection

To guarantee the **PCB** wasn't subjected to external force, which could damage the electronics, a board protection (figure 7.1) was created to transmit the applied force directly to the load cell while housing the **PCB**. The inclusion of the Board Protection in the load cell allows for a sturdy

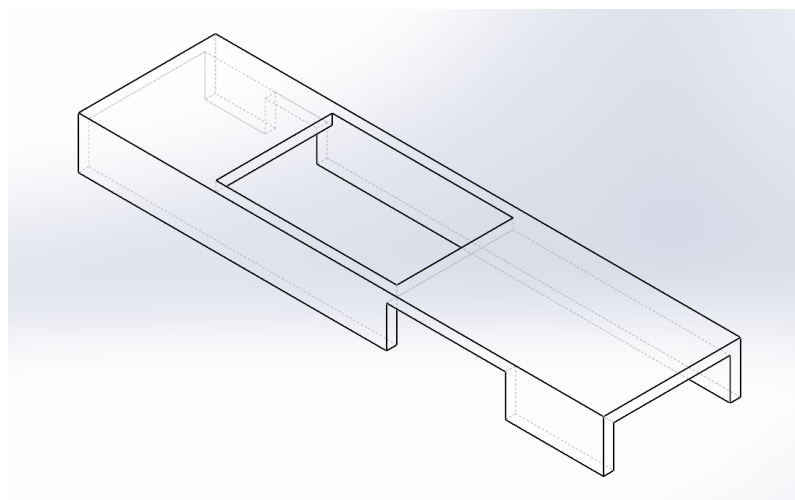


Figure 7.1: Isometric Drawing of the Board Protection

physical core, as the embedded electronics are protected, as seen in figure 7.2.

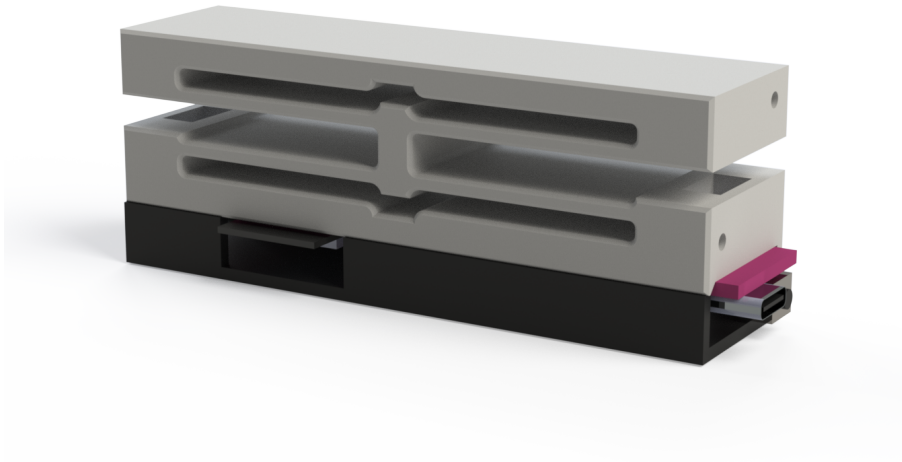


Figure 7.2: Load Cell and Board Protection

7.1.2 Cup Halves

The cup halves were designed to encapsulate the load cell, the electronics and the 500mAh battery. The outer aspect of the cup was developed as to maintain **SHaRe**'s dimensions, as these were optimized for an easy hand grip, while also accommodating the load cell, which meant a 17 mm base had to be added to the original design. A side by side comparison can be seen in figure 7.3.



Figure 7.3: New Prototype (left) and **SHaRe**'s design (right)

Each half of the encapsulation was meant to house the entire sensing system. As such, one part (known as the left side of the enclosure) was internally dimensioned to pressure fit the upper part the load cell, while the other (the right side of the enclosure) housed the bottom part, as well as the PCB, board protection and battery. Both parts have an undercut on the exterior to allow for the halves to be coated in fabric (figure 7.4).



Figure 7.4: Cup Halves, left side on the left and right side on the right.

7.1.3 Assembly

The Cup Halves were coated in *Scapa* 3514 tape [53] to provide a comfortable contact interface for patients to handle the prototype, as the original *SHaRe* prototype was considered to have too rough of a surface to grip due to the nature of 3D printing's layer by layer manufacturing. The tape was fixed with hot glue to prevent the coating from unsticking. In the right side of the enclosure, the battery was inserted and the board protection was pressure fitted (figure 7.5).

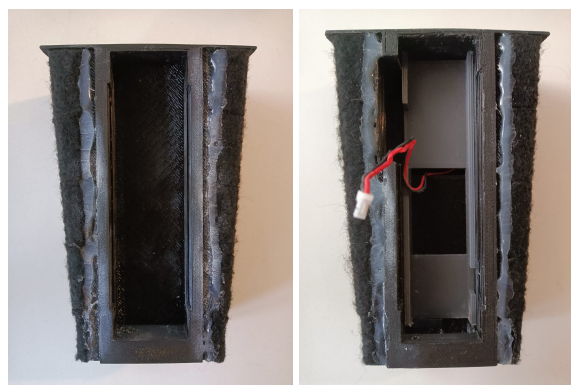


Figure 7.5: Left Cup Half coated with Scapa 3514 and Right Side with Battery and Board Protection

Afterwards, the circuit board was mounted on the load cell and the load cell was fitted into the left side of the enclosure. The battery connector was connected to the electronics (figure 7.6) and,

finally, the two cup halves were joined by fitting the bottom part of the load cell into the right side of the enclosure. Two 2.5 mm screws were screwed in to fix the load cell's position inside the cup (figure 7.6).

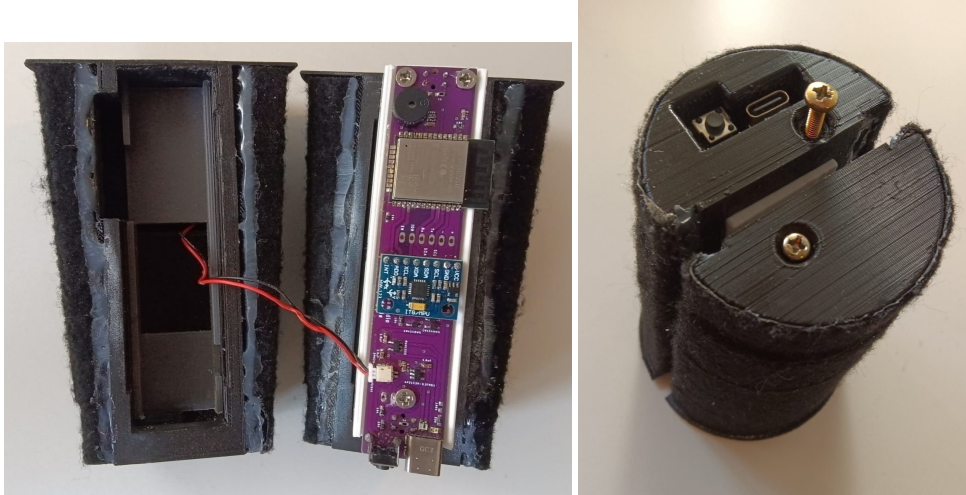


Figure 7.6: Connecting the battery to the electronics (left) and placing the bottom screws (right)

The final assembled prototype can be seen in figure 7.7.



Figure 7.7: Final Assembled Prototype

7.2 Validation Tests

The new prototype and corresponding game (as seen in chapter 6) were taken to therapy professionals in the School of Health of P. Porto to assess the system's performance and utility. For the

execution of the validation tests, two separate performance metrics were made: a written open answer satisfaction inquiry custom made to analyse the new prototype's improvements and shortcomings over the **SHaRe**, and a User Experience Inquiry that included the **SUS** [54] and the **UEQ** [55], two fast and reliable tools with standardized questions.

7.2.1 Satisfaction Survey with Professionals

This set of questions was made to provide a subjective but palpable comparison between the new prototype and the **SHaRe** while including questions about the new device's utility from a professional's point of view. The therapy professionals were asked to rate eight statements with a number between 1 and 5, with 1 meaning the respondent totally disagreed with the statement, and 5 meaning the respondent totally agreed. The statements were as follows:

1. The new cup's tactile feedback is beneficial to the rehabilitation process;
2. I found the new device to be more comfortable to the touch than **SHaRe**;
3. The inclusion of difficulty levels aids in the rehabilitation process;
4. The inclusion of sensitivity levels aids in the rehabilitation process;
5. I found the new device to be heavier than the **SHaRe**;
6. I found the device to be ergonomic;
7. The game/device set answers efficiently to the problems raised by hand rehabilitation;
8. The new device represents an improvement regarding the previous system, **SHaRe**.

While statements 1, 2, 5 and 8 are meant to compare the new prototype and **SHaRe** hardware-wise, statements 3, 4, 6 and 7 were included to provide some insight on the developed system. Another thing to note is that a value close to 5 (totally agree) is considered a positive value in all statements except statement 5, as the new prototype is meant to not only be but also feel lighter than the **SHaRe**, as this was one of the topics for improvement of the device. The inquiry also contained a field for respondents to post their additional observations.

7.2.2 User Experience Inquiries

As previously mentioned in section 7.2, the User Experience Inquiry was developed using two standardized tools: The **SUS** and the **UEQ**. This inquiry also collects personal data such as age group, gender, and level of education, to guarantee a wide range of attributes and characteristics in the inquired sample. Furthermore, the respondents were also asked to input their scores in each game, as to subsequently analyse the difficulty of each game.

System Usability Scale The **SUS** consists of 10 standardized statements that the respondent must rate from 1 to 5, with 1 being "Totally Disagree" and 5 being "Totally Agree". Originally created by John Brooke in 1986, it allows you to evaluate a wide variety of products and services, including hardware, software, mobile devices, websites and applications[54]. As such, it provides a reliable tool for the analysis of the new prototype system (device and game). After processing the obtained data, the **SUS** returns a score from 0 to 100, with scores above 68 being considered above average. The best way to interpret the results is to normalize the score to produce a percentile ranking, using available score databases.

User Experience Questionnaire The **UEQ** is a fast and reliable questionnaire to measure the User Experience of interactive products, and is available in more than 30 languages, allowing the questionnaire to be performed in Portuguese with the official translations [55]. It measures both classical usability aspects and user experience aspects. Thus, the main measures gathered from this questionnaire are:

- **Attractiveness:** Overall impression of the product;
- **Perspicuity:** Is it easy to get familiar with the product and to learn how to use it?
- **Efficiency:** Can users solve their tasks without unnecessary effort?
- **Dependability:** Does the user feel in control of the interaction?
- **Stimulation:** Is it exciting and motivating to use the product?
- **Novelty:** Is the design of the product creative?

The **UEQ** has two versions in a selected language: The complete version, with 26 items, and the short version, with 8 items. Data analysis tools are also provided in the official website [55] to process the data, getting results and comparing them to benchmarks. In the performed User Experience Inquiry, the complete version was used in its official Portuguese translation.

In total, 10 healthcare professionals and 10 common users responded to the User Experience Inquiry after testing the new prototype's system, totalling 20 responses.

This sample consisted of a heterogeneous demographic. Of the inquired users:

- 60% were females while 40% were males;
- 45% were aged 21 to 30 years old, with 15% being younger (18-20) and 35% being older;
- 85% had higher education.

7.3 Results

7.3.1 Satisfaction Survey Results

The Satisfaction Survey with Professionals produced not only valuable but also encouraging results. Table 7.1 contains all the answers with the statements numbered from 1 to 8, provided by the 9 inquired therapy experts, while table 7.2 provides the average and median values of responses.

Table 7.1: Satisfaction Inquiry Answer Distribution

Statement	Professionals' Answers								
1	4	5	4	5	5	5	5	5	5
2	4	5	5	4	5	5	5	5	5
3	4	5	5	4	5	3	4	5	5
4	4	5	5	4	5	5	4	5	5
5	2	1	5	2	1	4	1	2	1
6	4	5	4	3	5	4	5	5	4
7	4	5	4	3	4	4	4	5	4
8	4	5	4	4	4	5	4	5	5

Table 7.2: Average and Median Values of the answers provided

Statement	Avg	Med
The new cup's tactile feedback is beneficial to the rehabilitation process.	4.8	5
I found the new device to be more comfortable to the touch than SHaRe.	4.8	5
The inclusion of difficulty levels aids in the rehabilitation process.	4.4	5
The inclusion of sensitivity levels aids in the rehabilitation process.	4.7	5
I found the new device to be heavier than the SHaRe.	2.1	2
I found the device to be ergonomic.	4.3	4
The game/device set answers efficiently to the problems raised by hand rehabilitation.	4.1	4
The new device represents an improvement regarding the previous system, SHaRe.	4.4	4

From these results, it's possible to infer that:

- The 5 mm displacement of the new PETG load cell with optic sensors was considered to be an improvement over the isometric conditions of the SHaRe's single ended beam load cell;
- The process of coating the cup halves with fabric tape turned out to provide a more comfortable gripping area than bare 3D printed plastic;
- The inclusion of difficulty and sensitivity levels, absent from the original SHaRe's games, was considered to be beneficial for the hand rehabilitation process;
- Opinions were torn on if the new prototype felt heavier than SHaRe, but the overall impression was that the new prototype was lighter than SHaRe;
- The device was considered to be ergonomic;

- The entire system was found to answer to the problems raised by hand rehabilitation, with margin for improvement;
- The new device was, overall, considered to be an improvement over the SHaRe hardware-wise.

A set of four observations was also gathered from the Satisfaction Surveys with Professionals, which were translated to English:

- 'In a real rehabilitation scenario, this device will be more beneficial than the current "stress ball" as it requires the use of all 5 fingers, rehabilitating the fingers and even assisting with wrist joint movement'.
- 'The increased volume of the new cup contributes to a better feel. The weight of the cup is also better distributed due to this factor, resulting in a dynamic and pleasant experience.'
- 'The cup is suitable for rehabilitation. The requirements of the game need to be reviewed.'
- 'The sensory feedback is much better than the previous device.'

7.3.2 User Experience Inquiry Results

To interpret the results of the User Experience Inquiry, it's important to individually interpret the answers to the SUS and UEQ, as they provide different metrics of evaluation and different result presentation.

7.3.2.1 System Usability Scale Result

Out of the 20 inquiries, an average SUS score was obtained from using the standard scoring process [56] for each entry and calculating an average score. Thus, the final obtained score can be seen in equation 7.1:

$$SUS_{value} = \frac{\sum SUS_{user}}{number\ of\ users} = 80.9 \quad (7.1)$$

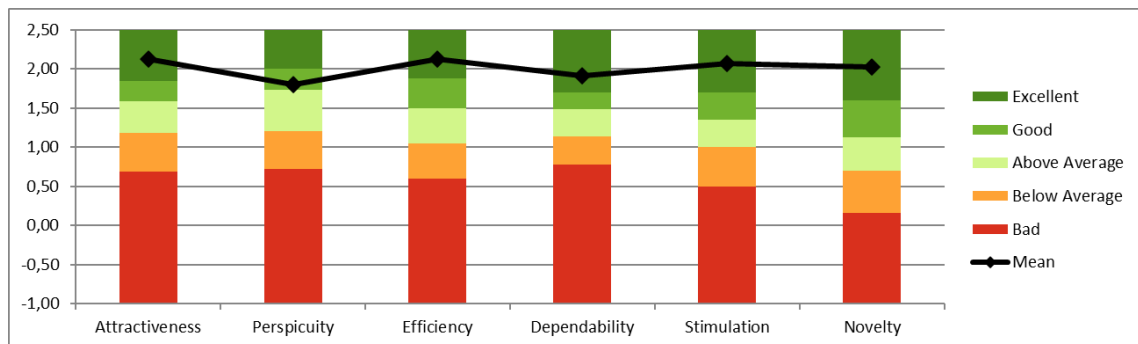
This average SUS score was then compared to the Curved Grading Scale (table 7.3), a grading scale for SUS that uses a wide database for grading while placing the SUS score of 68 in the middle of grade C, since the score of 68 is the average score of SUS [57]. From table 7.3, the SUS score of 80.9 can be ranked as a Grade A.

Table 7.3: Curved Grading Scale for the SUS (from [57])

Grade	SUS	Percentile range
A+	84.1 – 100	96 – 100
A	80.8 – 84.0	90 – 95
A-	78.9 – 80.7	85 – 89
B+	77.2 – 78.8	80 – 84
B	74.1 – 77.1	70 – 79
B-	72.6 – 74.0	65 – 69
C+	71.1 – 72.5	60 – 64
C	65.0 – 71.0	41 – 59
C-	62.7 – 64.9	35 – 40
D	51.7 – 62.6	15 – 34
F	0 – 51.6	0 – 14

7.3.2.2 User Experience Questionnaire Result

The results were analyzed using the Data Analysis Tools provided in the **UEQ** website [55]. By inputting the data, the Data Analysis Tool ranks the product based on Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation and Novelty and compares it to benchmarks from the **UEQ** database. A graph showing the product's comparison to the benchmarks in each category can be seen in figure 7.8.

Figure 7.8: New System Comparison to **UEQ** benchmarks

From figure 7.8, it's possible to infer that:

- The users were overall very impressed with the product;
- The system was not too easy to learn and to get familiar to;
- The tasks were easily performed without unnecessary effort;
- The users felt in control of the interaction;
- The product was considered to be exciting and motivating to use;
- The users considered the product to be creative.

7.4 Discussion

Overall, the results from the Satisfaction Survey with Professionals and the User Experience Inquiry were very promising.

From the Satisfaction Survey, we can clearly see a perceived improvement over the original system, **SHaRe**, and the development of a load cell with 5 mm of displacement for a load of 5 kgf was instrumental for this perception.

A positive result can also be found in **SUS**, as the system's usability was considered to be above average. Finally, the **UEQ** also provided encouraging results, as the User Experience was considered to be Excellent in all fields except Perspicuity. In the field of hand rehabilitation, it's important for devices and interfaces to be as familiar and intuitive as possible, so it's important to increase the device's transparency for regular audiences.

Chapter 8

Conclusions and Future Work

This document explored the conception, development, assembly and testing of a new hand grip training system based upon the **SHaRe** prototype developed by the University of Porto. This work seeks to introduce a simple system that makes use of Serious Games for home-based hand physical therapy, attempting therefor to increase patient compliance with the rehabilitation process.

Initially, the document introduced the context and motivation of this dissertation while emphasizing the theme's relevance. Subsequently, various topics related to the theme of hand rehabilitation were explored in a literature review, highlighting pertinent information.

The review strove to assess the currently available devices and technologies in the field of hand rehabilitation. In doing so, an important observation was found: despite the multiple commercially available devices with gamified elements there appears to be a severe scarcity of hand grip training devices developed specifically for the assessment and training of lower values of grip strength targeted to patients with severe hand impairment, as is the case of stroke victims, multiple sclerosis patients, and prosthetic hand users.

The **SHaRe** prototype by the University of Porto was designed to fill in this void, and, following up on the literature review, the multiple published articles on the subject were consulted to provide a comprehensive overview of the system's advantages and shortcomings. The system, with its game-based approach, has had promising results in patients' compliance with therapy, with improvements in perceived grip force after using **SHaRe** for multiple sessions. However, the need to improve force readings and ergonomic handling became apparent, as well as the opportunity to replace the custom made single ended beam load cell with a lighter and cheaper alternative with sensors that allowed for the assessment of millimetric deformations, which would provide the handler with a tactile feedback of his or her own force.

Then, the document described the new system's development in four stages: the creation of a new sensing solution, the implementation of embedded electronics and firmware, the creation of a Unity-Based Game and the final assembly of the cup-shaped prototype.

A custom made **PETG** load cell equipped with optic sensors was developed for this new prototype, providing a reliable force measurement solution that also delivered tactile feedback to the user, compressing 5 mm for a 5 kgf load.

This sensing solution was complemented with embedded electronics and custom firmware, allowing the device to send the measured data through BLE. The final result presented an almost linear behaviour to force compression, with a resolution of 20gf. A unity-based Android serious game was created to complete the system, providing a visual interface for the users to use the device. The final device was assembled to maintain the SHaRe's cup-like design.

The new system was demonstrated to therapy experts, and yielded promising results for future implementation in clinical trials. A User Experience Inquiry was also conducted, based upon the SUS and the UEQ, with a broader audience. These questionnaires brought forth some points for improvement, such as accessibility and overall intuitiveness. The included minigames were also considered to be too difficult for a rehabilitation setting, despite the inclusion of difficulty levels.

All the designed parts of the device will be available as appendices.

Lastly, the upcoming sections will outline this dissertation's main contributions, as well as further improvements to this prototype.

8.1 Main Contributions

Among the multi-disciplinary contributions of this dissertation, the most note-worthy is the development of a working 3D printed load cell equipped with optic sensors. This new and innovative sensing system allows for reliable force measurements without compromising resolution, and can easily be mass manufactured at lower prices than traditional load cells. This new approach to hand grip training devices will allow for future production of cheaper, comfortable and effective devices for patients to use in a home therapy setting. Furthermore, this approach to force measurement may also be expandable to other load sensing devices, such as scales.

In addition, the development of this project may provide a major contribution to the hand grip training device market, as it attends to the needs of patients with little to no hand grip control, a severely overlooked demographic.

8.2 Further Improvements

Despite the attempt to make a fully functional product, there is still much work to be done with this prototype to achieve its full potential. To achieve the same level of functionalities as its predecessor, SHaRe, the inclusion of games that make use of the device's IMU would be welcomed, as it allowed patients to not only train hand grip, but also hand movement. Games should also be rethought to present a smaller learning curve, as well as be overall easier for hand patients. Engagement tools, such as audio feedback and reward systems may prove to be a major contribution in the future. Additionally, the ESP32 module used for fast prototyping and programming should be replaced by more standard, cheaper alternatives. Regarding the load cell, a PET design for plastic injection molding would contribute to a cheap and mass-producible sensing solution. Finally, the PLA plastic parts that integrate the cup-shaped device should also be revisited for plastic injection molding in alternative plastic material.

8.3 Future Work

Overall, the inquiries with professionals and generic end-users yielded very promising results for this system's implementation in a therapy setting. However, for the new prototype to be eventually used, further studies are required. A broader sample of end-users must be inquired the user experience to be accurately assessed and thus refined. Furthermore, this system should be subjected to clinical trials with patients suffering from hand disabilities, as its real contributions in hand rehabilitation are yet to be tested.

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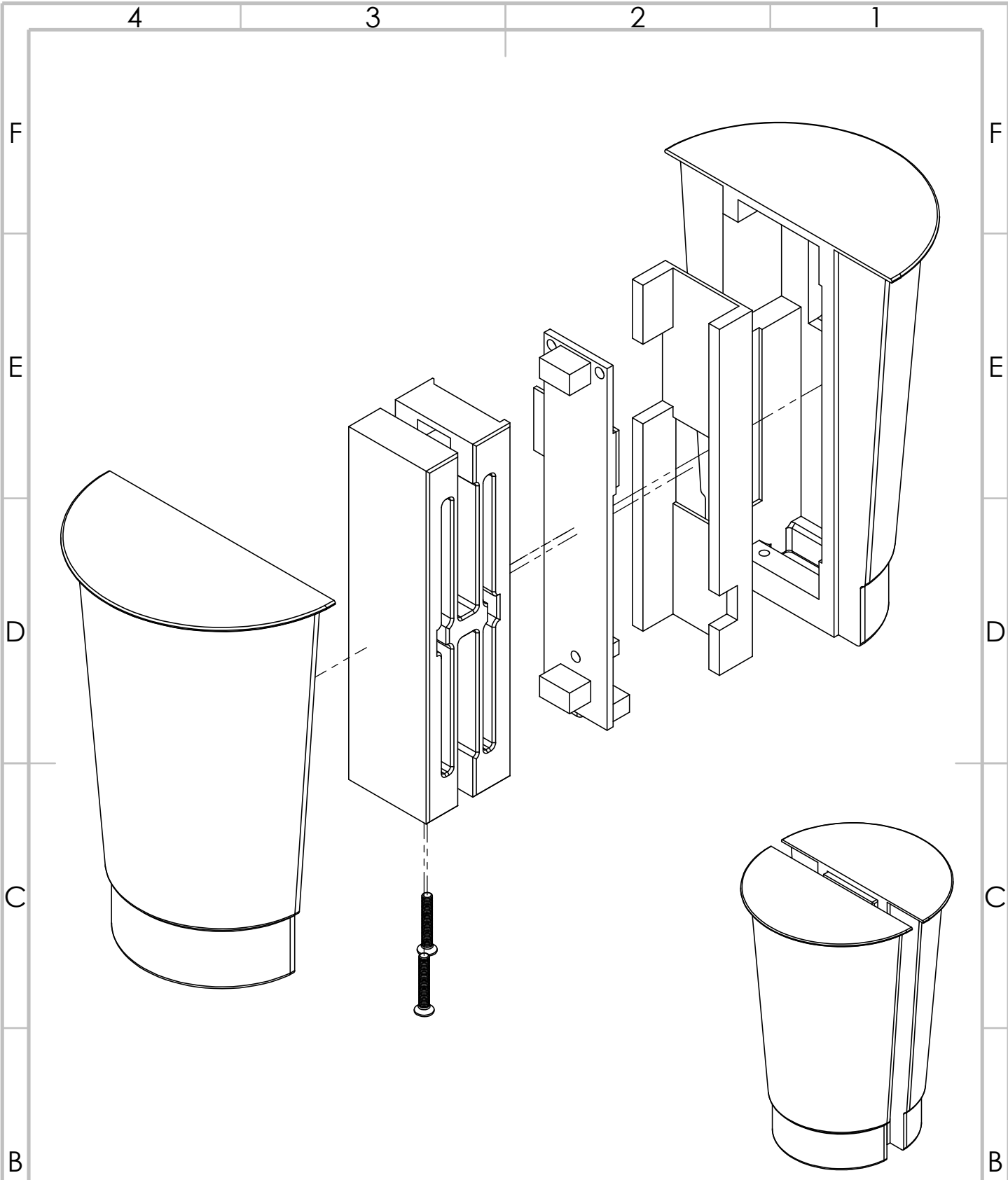
Appendix A

Appendix

A.1 Mechanical Project



Figure A.1: Final System Prototype



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

MATERIAL:

WEIGHT:

TITLE:

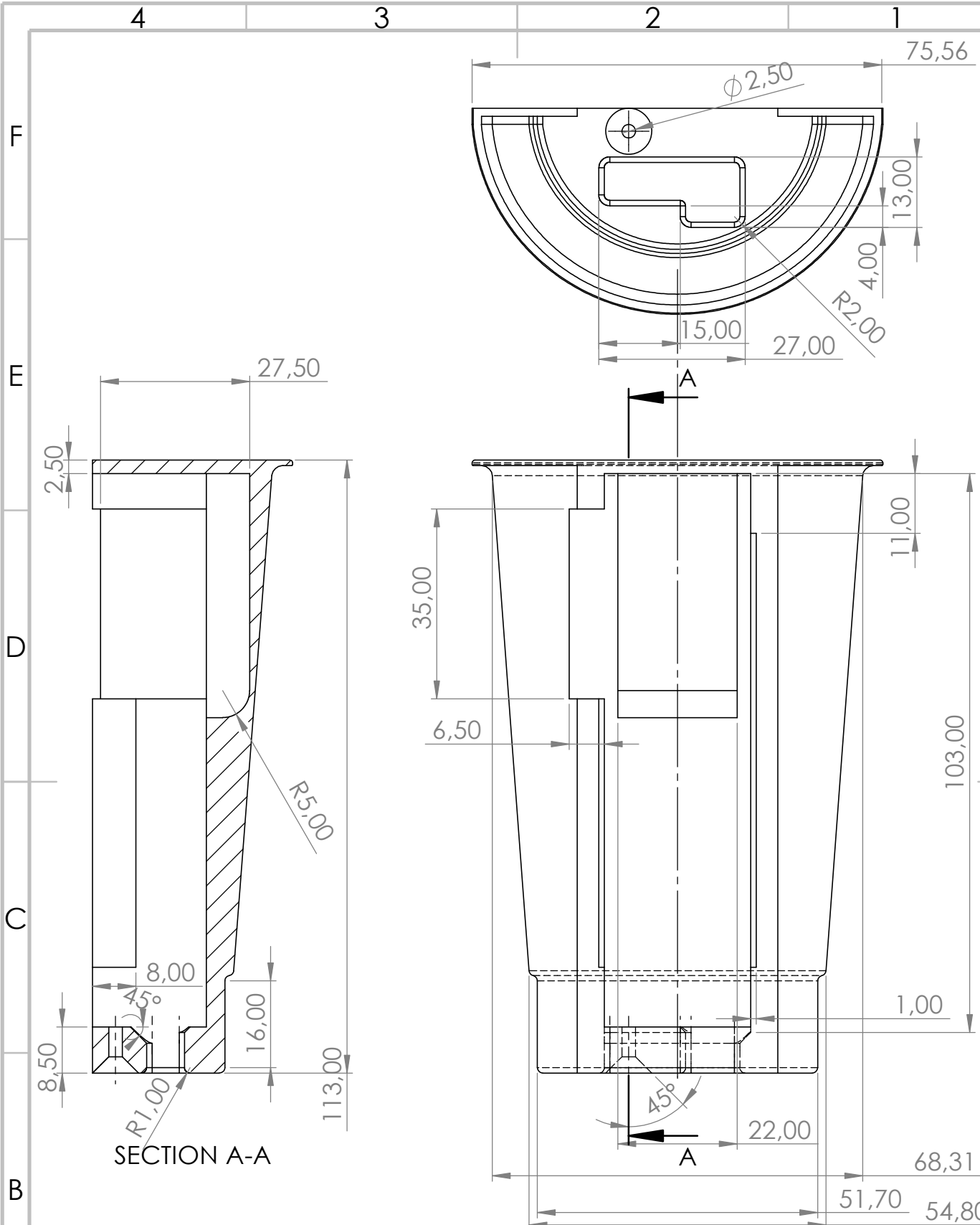
DWG NO.

Exploded View

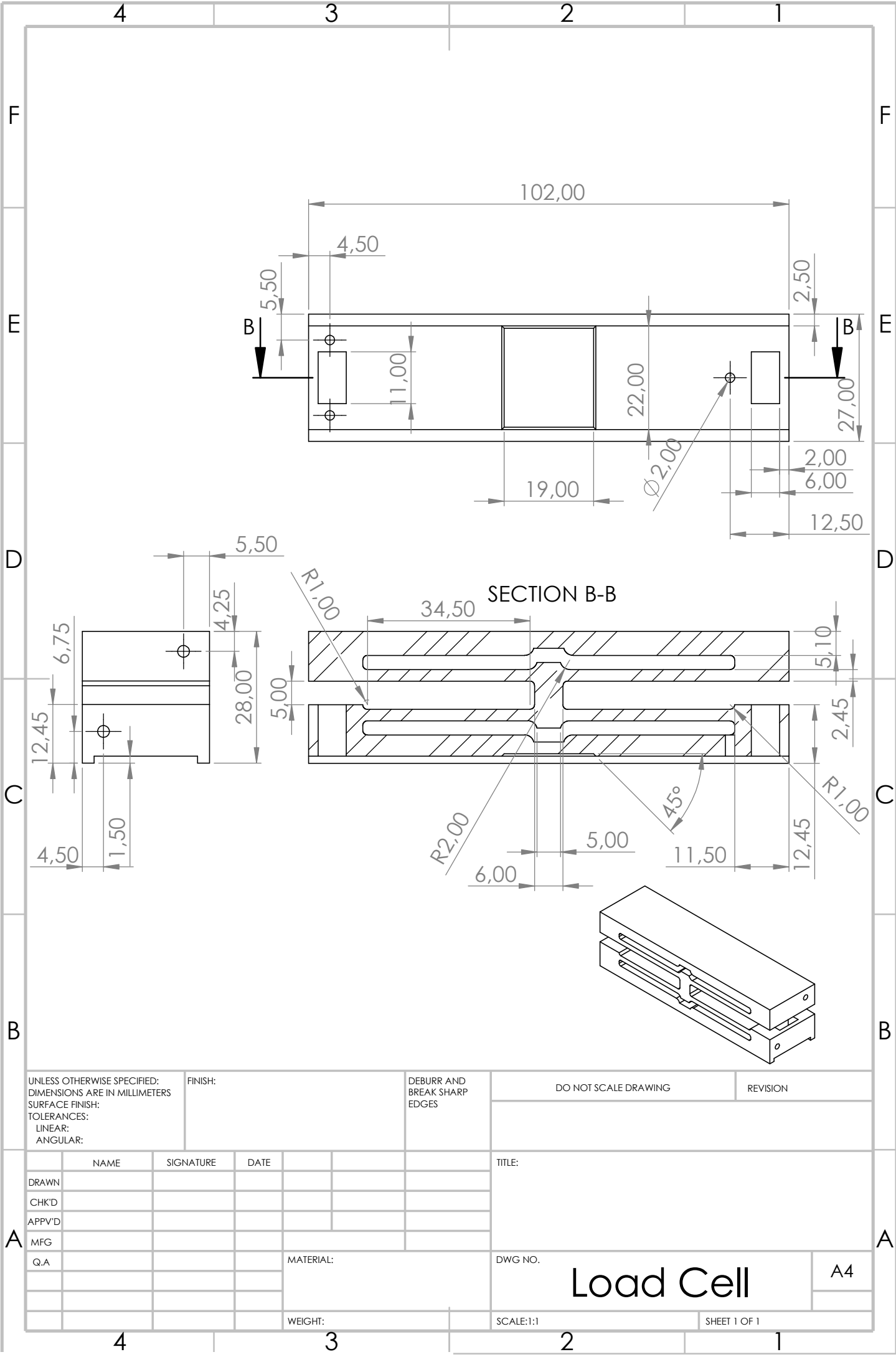
A4

SCALE:4:5

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:				FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING		REVISION	
		NAME		SIGNATURE		DATE				TITLE:	
DRAWN											
CHK'D											
APPV'D											
MFG											
Q.A								DWG NO.		A4	



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

MATERIAL:

WEIGHT:

TITLE:

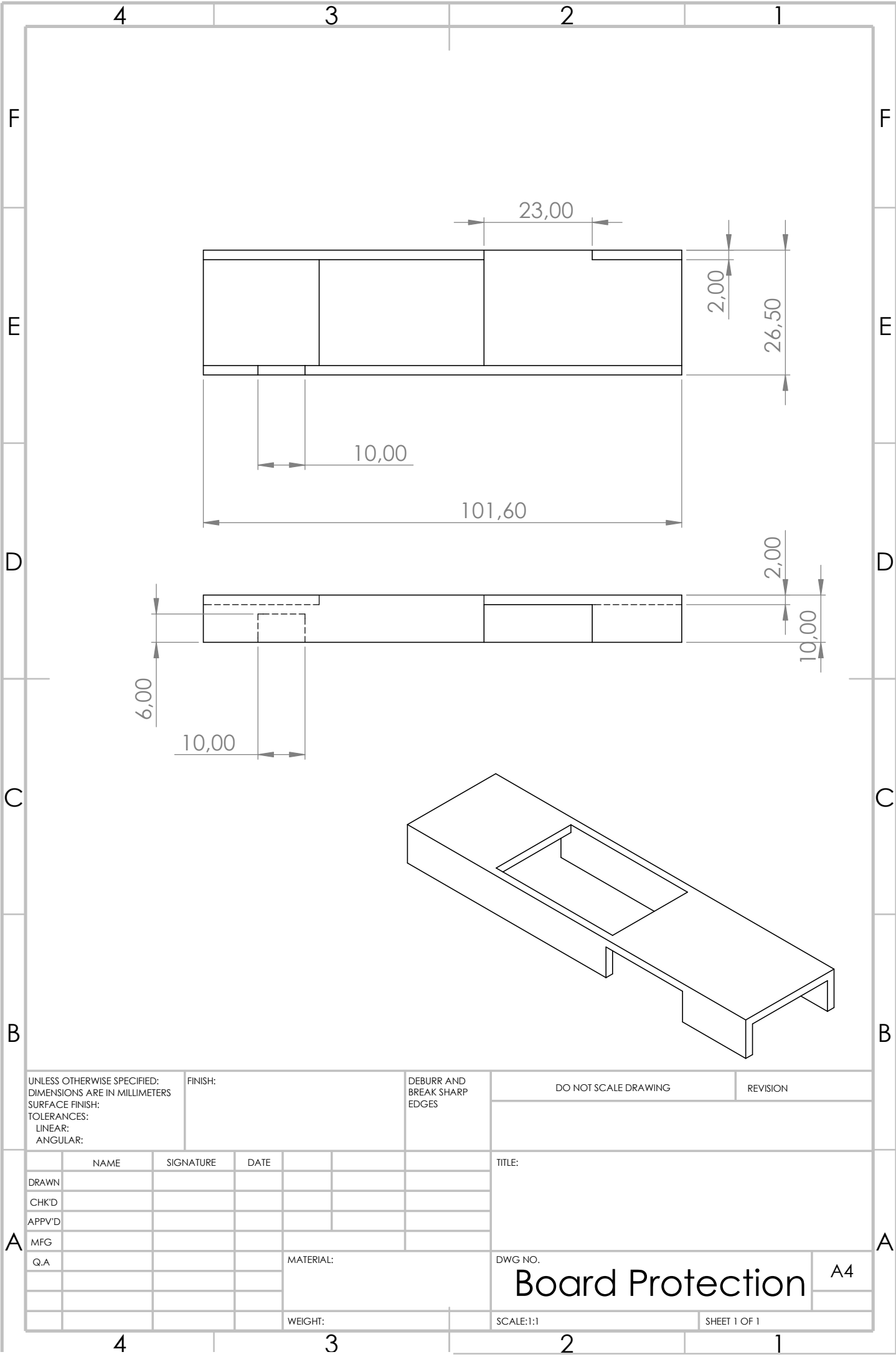
DWG NO.

SCALE:1:1

SHEET 1 OF 1

Load Cell

A4



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

MATERIAL:

WEIGHT:

TITLE:

DWG NO.

Board Protection

A4

SCALE:1:1

SHEET 1 OF 1

