Bachelor's Thesis

Interactive glove for mobility training and rehabilitation after stroke

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Preface

This bachelor's thesis contains work completed between March and June 2016 at Certec, Lund University, Sweden.

Several people have helped to contribute to the project.

I would like to thank my supervisor, Héctor Caltenco, for his valuable ideas, support and feedback throughout the entire project.

Furthermore, I would like to thank everybody who agreed to come and test the product. The feedback given was really helpful and has been taken into consideration during the design process.

Lund, June 2016

Mihkel Hiob

Abstract

Stroke affects a vast amount of people every year. As a result, many survivors have at least partially lost some of their abilities which are necessary to complete everyday activities. Although rehabilitation can be used to improve those abilities, many survivors claim that conventional methods are demotivating and discouraging.

The aim of this project is to develop and test interactive objects, which would implement activities that are scientifically proven to have good effects for stroke rehabilitation. Different exercises for stroke rehabilitation have been studied and their feasibility of implementation evaluated. Furthermore, previous research and a few existing solutions are also presented in this paper.

This thesis describes creating a glove using an iterative design process, which would implement several hand exercises to control a computer's mouse and keyboard. The core of the glove is the Arduino Leonardo microcontroller, which is connected to different sensors sewn into the glove. Hand exercises, such as wrist extension and flexion or finger lifting, are used to control the computer in a simple way. For example, to simulate an arrow key keystroke, the user has to apply pressure on his/her fingertips where force sensors are located.

The final prototype was tested by multiple people. Although the user experience and functionality of it could be improved, all participants said that they enjoyed using the device. Hence, using the results from this project as well as from previous research, it can be concluded that interactive objects can be motivational and encouraging for mobility training and stroke rehabilitation.

Keywords: stroke, rehabilitation, interactive objects, Arduino, interactive design

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1 Introduction

This chapter provides background information concerning strokes and the project. Descriptions are provided regarding what strokes are, its impacts and rehabilitation. The motivation and aim of the project are also introduced in this chapter.

1.1 Strokes

Stroke is a cerebrovascular disease which occurs when the blood supply to the brain is cut off. In 2013, about 32.2 million people suffered from a stroke worldwide, 6.5 million of whom died [1].

The American Stroke Association [2], among other sources, identify a number of risk factors for stroke:

- Age
  Stroke usually affects older people, although there is a significant number of younger people who also suffer from strokes. After the age of 55, the probability of having a stroke doubles for each decade.
- Heredity
  Stroke may be caused due to a gene mutation. Hence, the chances of having a stroke are higher if a close relative has suffered from it.
- Race
  Black people have the highest risk of death from a stroke as the probabilities of having high blood pressure, diabetes and obesity are greater.
- Gender
  Women are generally more likely to have a stroke than men.
- Other diseases
  Artery and heart diseases, high blood pressure and cholesterol, diabetes and many other heart conditions increase the chance of having a stroke.
- Bad habits
  Smoking, alcohol and drug abuse, poor diet, physical inactivity and obesity increase the risk of different diseases and stroke.
- Geographic location
  Strokes are more prevalent in developing countries than in developed countries [3]. While the main cause of strokes in developed countries is ageing, the increase in prevalence in developing countries is due to smoking, obesity and not being able to prevent a stroke due to lack of modern medical devices [4].
- Socioeconomic factors

> Previous studies have shown that strokes are more common among lower income people.

There are three types of strokes: ischaemic stroke, haemorrhagic stroke and transient ischaemic attack (TIA) [5]. Firstly, an ischaemic stroke occurs when the blood supply to the brain is cut off due to a blockage and accounts for about 87 percent of all cases [6, 7]. The blockage can be caused by a blood clot developing at the clogged part of the vessel, which is known as cerebral thrombosis. A blockage can also be caused by a blood clot or other matter formed at another part of the circulatory system, which is known as cerebral embolism [6]. Secondly, a haemorrhagic stroke results from a burst of a blood vessel which causes bleeding in or around the brain and can be more dangerous than an ischaemic stroke [8]. Thirdly, a TIA is caused by a temporary clot [5]. Although the symptoms of a TIA may not last too long, it should be taken very seriously as it may be a warning sign of a heart condition.

1.2 Stroke impacts and rehabilitation

As a result of a stroke, the nerve cells in the affected area are damaged, and without oxygen, they start to fail and die after a few minutes [9]. This causes parts of the body that the cells control to stop functioning, resulting in motor, sensory and cognitive problems. The effects are often permanent because dead brain cells are not replaced [10]. Hence, depending on where a stroke occurs and the extent of brain tissue affected, one may have problems with moving the right side of the body, talking or understanding speech (all controlled by the left side of the brain), vision or moving the left side of the body (both controlled by the right side of the brain) [11]. When a stroke occurs in the brainstem, it can affect eye movement, swallowing, breathing, alertness and other specialised functions [11].

Due to the resilience and capabilities of the brain, it is possible to recover at least some functionalities. Rehabilitation is an integral part of the recovery process and begins at the hospital. It usually consists of physical, cognitive, emotional activities and experimental therapies [12]. However, rehabilitation is different for each person, as the type and severity of the stroke, general health, personality and other support received, e.g. from family, need to be considered [13].

The goal of rehabilitation is to decrease the effects of a stroke in order to regain independence and to attain the best potential quality of life, e.g. being able to do everyday activities such as cooking, getting dressed and washing. Not all stroke survivors need rehabilitation because of the low impact of a stroke, such as a TIA, but those who do are expected to complete a number of activities over a period of time. This involves many passive and active exercises. Passive exercises are those where a patient is helped and assisted by a therapist, while active exercises are performed by the patient independently [14]. In order to achieve the best outcome, both methods should be combined. However, since rehabilitation might take months or years depending on the severity and type of stroke, the repetitive nature of the exercises may become frustrating. Furthermore, it is very difficult to stay motivated if progress is not immediately evident. According to a study, only 31% of stroke survivors perform home exercises prescribed by therapists due to a lack of motivation and slow progress [15]. Hence, technology-assisted rehabilitation has become more widespread in recent years to make the training easier, enjoyable, more motivating and encouraging [16].

The most common physical impact of stroke is loss of limb movement and muscle weakness [17]. For example, about 85% of people have problems with arm movements after a stroke [18]. Hence, motion exercises are very common in order to strengthen stroke impaired limbs [14].

1.3 Motivation

Stroke affects millions of people around the world every year. Those who survive have generally at least some partial disability and hence may not be able to complete some everyday activities such as cooking, cleaning, washing, etc. For example, a study conducted by Wade and Hewer [19] revealed that 88% of people surveyed relied on other people to perform everyday activities. This was determined by using the Barthel index [20], a 20-point scale used to measure performance in activities of daily living, one week after a stroke. Anything less than 20 points indicates dependence on others. Hence, many people rely on rehabilitation in order to recover at least some of their previous abilities. Since constant exercising is important, being dedicated and motivated is vital in order to achieve the best result possible. Therefore, rehabilitees should also perform active exercises at home. However, they may not be confident enough and give up on rehabilitation which in turn may lead to incomplete recovery. Additionally, a study conducted in the United States by Shaughnessy and Resnick [21] found that 69% of stroke survivors do not perform all of the required or prescribed exercising at home due to a lack of self-efficacy and motivation. Furthermore, the repetitive nature of activities may also make them boring and rehabilitees may lose interest in performing them. Thus, interactive objects that motivate performing such exercises could be used to help in stroke rehabilitation. Their flexibility can be used to implement multiple activities in an interesting and motivating way, e.g. in order to change the TV channel, a user has to perform an exercise beforehand. Therefore, it might help to keep the motivation up and in turn result in better recovery. However, it should be kept in mind that not all stroke survivors value the same things, and hence not all of them find the same exercises motivating. Furthermore, by creating interactive objects which are easy to use, giving clear instructions and feedback, survivors can be confident that they are performing exercises correctly. Unfortunately, interactive objects are not very widely used for stroke rehabilitation, but seem to be growing in popularity.

1.4 Research questions

How can interactive objects be successfully used to implement stroke rehabilitation exercises?

How can interactive objects make performing repetitive tasks more fun and motivating compared to performing them without any assistive objects?

1.5 Aim

The aim of this project is to develop and test an interactive object which would implement an activity that is already known to have good effect for stroke rehabilitation. The interactive object should be robust, relatively compact, easy to handle and should arouse one’s interest in using it. However, since many stroke survivors find rehabilitation exercises rather boring and frustrating, one of the main goals would also be that the interactive object would motivate them and make performing exercises easier.

Age, physical and mental abilities as well as open-mindedness towards technology vary a lot among stroke survivors. Hence, another goal of this project is to develop an interactive object which could serve a vast amount of people.

2 Theoretical background

This chapter summarises some of the research on the field, as well as gives examples of products already used for stroke rehabilitation. Some rehabilitation exercises are also presented in this chapter. Furthermore, it gives an overview of tangible interaction and how it is taken into account when designing interactive objects for stroke rehabilitation. The concept of vertical and horizontal prototyping is introduced at the end of the chapter.

2.1 Research on designing for stroke survivors

As some studies have shown, many stroke survivors are unmotivated or unconfident to perform rehabilitation exercises at home. Hence, the amount of research on the field is constantly increasing in order to find ways to make rehabilitation more motivating by the use of technology. This usually involves stroke survivors early in the design and testing processes to determine what they appreciate about a product and what could be improved upon.

Axelrod et al. [22] carried out a project where they found that many elderly people living with stroke could not see the benefits of technology, or that they were not confident enough to use it due to over-complications. This is confirmed by a study by Bjørkquist et al. [23] where elderly stroke survivors say that they do not feel entirely comfortable with using telecare or telehealth technologies, but nevertheless would be willing to use it if it would help them with stroke rehabilitation. As some rehabilitation products might also need extra technology, e.g. a TV, some people were also concerned about financial implications and extra space needed [22, 24]. Hence, stroke rehabilitation products should not look very technical, and they should have enough guidance such that stroke survivors would be comfortable and capable of familiarising themselves with them. Furthermore, there should also be motivation as well as space to perform physical exercises.

Curtis et al. [25] developed interactive games which would help stroke survivors with handwriting rehabilitation. There were four games with adjustable levels of difficulty. A user-centred design approach was used to target both stroke survivors and healthcare specialists effectively. The application also provided a performance history, audio-visual feedback, and posture reminders. Finally, the preliminary results show that the games were both fun and motivating.

Balaam et al. [26] carried out a study where they worked closely with a few stroke survivors and developed products which the participants thought they would find interesting. In the beginning, the participants used their products actively, however, after a while some stopped using them as often because they claimed that doing the same thing became boring. Some participants also reported that they did not like the aesthetics of the products and thought that they would not fit in with their homes [24, 26]. Hence, it is important to have deep discussions with stroke survivors in order to determine what they are interested in and involve them in designing and prototyping stages so that the final product could be tailored according to their needs [23, 24, 26]. It is also important to consider other factors such as work and free time as well as where and when the product will be used, and what other support is available, e.g. family members [24, 26].

Delbressine et al. [27] designed a tangible table-top interaction with wearable technology which would help rehabilitees with arm-hand rehabilitation by performing grasping exercises. Many survivors reported that they both enjoyed using the object and have found it to be useful as well. Furthermore, a study conducted by Michaelsen et al. [28] shows that stroke rehabilitation might even be very beneficial for stroke survivors with chronic hemiparesis.

Timmermans et al. [29, 30] have evaluated the feasibility and effects of technology-supported task-orientated arm training (T-TOAT) and how it affects survivors' motivation. The method comprises of separating training skills into functional components such that the relationship with the original training skill is retained. Figure 2.1 shows how skills such as drinking from a cup or eating with a knife and fork are decomposed. The difficulty of each exercise is gradually increased based on principles of exercise physiology and motor learning. Decomposing skills gives the ability to implement exercise programs in technology-supported training. Participants start with training on components individually, and after a while, the complete action is trained. Timmermans et al. tested the method on nine chronic stroke survivors over an eight-week training period. The results show that the method significantly improved arm-hand performance as shown by mean values of Fugl–Meyer (14.2% improvement, $p < 0.001$), ARAT (15.3% improvement, $p < 0.05$), MAL-AU (43.4% improvement, $p < 0.05$), and MAL-QU (34.1 % improvement, $p < 0.01$), and the results lasted after the training. Furthermore, the participants claimed that their quality of life had improved, their motivation levels were higher and the system was easy to use. Thus, the method is feasible and has positive effects on stroke rehabilitation.

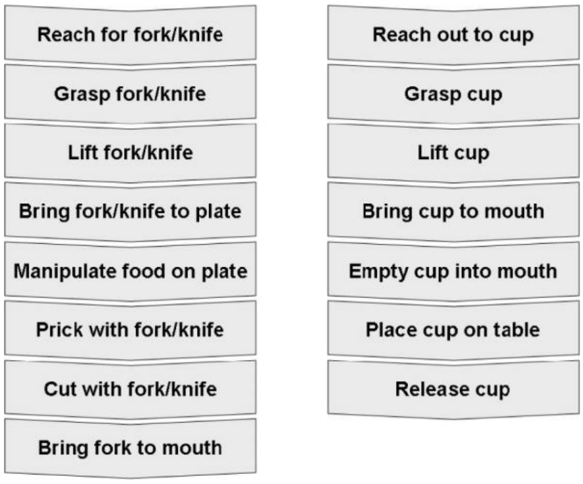

Figure 2.1 T-TOAT: decomposing skills [30]

Fitzpatrick et al. [24] mention that when designing an interactive object, it is also important to consider the following:

- Balancing needs and wishes, e.g. rehabilitation versus what the patient likes to do.
- Respecting the patient, i.e. what, how and when they want to do something.
- Determining what is fun and motivating for rehabilitees.
- Using a general design which would then be modified to specific needs.
- Creating a design which would be motivating in the long-term and flexible enough to adapt to changing rehabilitation needs.

Therefore, stroke survivors are interested in exercises which would relate to their favourite activities, e.g. reading books or playing chess, making them feel confident, allowing them to be active and also involving other family members. All of this will be taken into account during the designing stage.

2.1.1 ActivABLES

ActivABLES: Tangible Interaction to Support Effective and Usable Stroke Rehabilitation at Home [31] is a project carried out at Certec, researching on how physical and interactive objects can be used to make post-stroke rehabilitation easier and more motivating. The project tries to develop tangibles which would implement exercises already known to have a good effect on rehabilitation and help with rehabilitation by incorporating them into stroke survivors' daily lives [31]. The project has four objectives [32]:

1. Investigating how different design methods can be used to create rehabilitation tools which would be useful, enjoyable and motivating by involving stroke survivors as well as other people such as caretakers in the design process.
2. Developing interactive objects which would use multimodal feedback.

3. Developing software which would incorporate interactive objects in daily activities such as controlling the TV.
4. Investigating how interactive objects can be incorporated into stroke survivors daily lives and their support networks in an effective way, e.g. to keep rehabilitees motivated.

The project follows a user-centred design by conducting interviews and focus groups with stroke healthcare professionals, stroke survivors and their families [33]. Interviews with stroke healthcare specialists have revealed that in order to get good results, exercises should be meaningful, performed in context and part of an activity [33]. Furthermore, it was found that reminders of performing an exercise are important as well [33]. As already mentioned, the interviews have confirmed that exercising should be fun, motivating, safe, individually tailored, and also balanced, i.e. not too little but not too much either [33]. Furthermore, interactive objects should also be empowering and encouraging, aesthetic, simple and easy to use [33].

2.2 Existing solutions

There are a number of solutions already developed for stroke rehabilitation. This includes wearables which the user cannot interact with and is mainly used for measurements, e.g. muscle strength. An alternative solution is interactive objects that are used for exercising. Furthermore, some devices can be used for both measurements and exercising, or just to help with specific things, such as walking. Hence, interactive objects can be very encouraging whilst performing active exercises. However, the biggest disadvantage amongst solutions currently is the lack of specialised equipment [34].

Neofect in South Korea has developed a smart glove to help people with neurological brain injuries and hand rehabilitation [35]. The wearable glove, shown in Figure 2.2, comes with a software application that can evaluate a range of motions as well as analyse motions of the fingers and hand [35]. Additionally, it provides the user with a number of game-like exercises which implement various functional movements, such as those related to daily tasks (wrist flexion/extension, forearm pronation/supination, radial-ulnar deviation, and finger flexion/extension), in an effective and fun way [35, 36]. The software adjusts the level of difficulty of a game according to the learning schedule algorithm which tries to balance between challenge and motivation [35]. The games database is updated monthly and consists of games like squeezing an orange, pouring wine, catching balls or painting fences [36, 37]. Rehabilitees are also able to see their performance results, such as their current state and improvements, in a visual way [35].

Figure 2.2 RAPAEL Smart Glove™ [38]

The glove itself uses an Ultra-low-power ARM Cortex-M3 microcontroller, bending sensors (variable resistors) and a 9-axis inertial measurement unit which measure individual movements. The data is sent wirelessly to a computer via Bluetooth [35]. Furthermore, it is ergonomic and weighs only 132 grams [35].

Shin et al. conducted a study [36] where 46 stroke survivors were either using the glove or conventional intervention for hand and arm rehabilitation. The study showed that those using the glove improved significantly while the stroke survivors using the conventional intervention method did not make any significant improvements. Hence, it can be said that interactive objects have the potential in motivating rehabilitees as well as being more effective.

Bioness is an American company which designs devices for people with stroke, multiple sclerosis and other central nervous system disorders in order to regain mobility and independence [39, 40, 41]. The company has developed three products for stroke rehabilitation: the L300 for foot drop, the L300 Plus for foot drop plus thigh weakness and the H200 for hand paralysis therapy [39].

The L300 foot drop system, shown in Figure 2.3, uses wireless technology that senses how a person is walking and automatically adjusts to changes in terrain and walking speed [42]. It stimulates the nerves and muscles to lift the foot in order to walk more naturally [42]. The L300 Plus system adds a thigh cuff which helps to reduce thigh weakness and increasing control over bending and straightening the knee [43]. The H200 system, shown in Figure 2.4, uses wireless technology to help rehabilitees with regaining hand function such as reaching, grasping, opening and closing the hand [44]. Two studies by Hausdorf and Ring [45, 46] have confirmed that both L300 systems significantly improve stability and walking speed compared to not using them.

Figure 2.3 The L300 Foot Drop System [47]

Figure 2.4 The H200 for Hand Paralysis [48]

Saposnik et al. [49] used the Nintendo Wii gaming system to determine if it is feasible, safe and efficacious for arm rehabilitation after a stroke compared to recreational therapy. The system consists of a wireless controller and an infrared sensor. While the user moves the controller with their arm, hand and wrist, the sensors inside the controller measure speed, direction and acceleration, which are then sent to the system. It is computer assisted and hence does not require big sweeping movements. A TV screen provides real-time feedback, i.e. movements, and games are therefore fun and motivating to perform. The study showed that using the Wii for rehabilitation was more efficient than recreational rehabilitation as people were faster and had stronger grip.

2.3 Hand exercises for stroke rehabilitation

There are many exercises which can help with stroke rehabilitation. However, since the majority of stroke survivors suffer from problems with their hands, only those related to that are presented. Furthermore, as will be discussed in the upcoming chapters, this project deals with hand rehabilitation.

Figure 2.5 shows a wrist exercise. This involves lifting the wrist up, down and sideways [50, 51]. Hence, the instructions for this exercise are quite straightforward and easy. Furthermore, the other hand can be used to help with this exercise.

Figure 2.5 Wrist flexion and extension [50]

Another exercise is a wrist motion exercise. This involves turning the wrist in circles, as shown in Figure 2.6, to encourage greater motion in the wrist [50]. Again, this exercise does not require remembering many instructions.

Figure 2.6 Wrist supination and pronation [50]

It is also important to strengthen the finger muscles. This can be achieved by performing finger flexion and extension exercises. One of them is shown in Figure 2.7. The exercise consists of bending the fingers of the weaker hand into the palm and then straightening them out again [51]. Another finger exercise is to lift fingers up and down, as shown in Figure 2.8 [52].

Figure 2.7 Finger flexion and extension [51]

Figure 2.8 Finger lifting [52]

Many daily activities, such as holding heavy pans or opening jars, rely on grip strength. Hence, the grip exercise shown in Figure 2.9 can be helpful to improve flexibility and suppleness [53].

Figure 2.9 Grip strengthening [53]

2.4 Tangible interaction

Tangible interaction is an interdisciplinary field that studies user interfaces that are physically embodied, i.e. when physical objects are used to interact with digital information. For example, moving the computer mouse on a surface also moves the pointer on the screen. Hence, tangible interaction is a great tool for stroke rehabilitation as it provides instant feedback which both encourages and motivates exercising. Thus, the following should be considered when designing tangibles for stroke rehabilitees:

- Weight – physical object should be light so that the user does not feel uncomfortable or become tired quickly.
- Size – smaller objects are generally easier to handle.
- Aesthetics – the object should be reasonable and fit in at home.
- Simplicity – instructions should be clear and easy to follow.
- Feedback – the user should be aware whether he or she is using the object in a correct way.

Hornecker and Buur [54] say that tangible interaction share the following characteristics:

- Tangibility and materiality – the user should be able to hold or touch the object which uses senses, such as audio or visualisations, to give feedback.
- Physical embodiment of data – digital information is represented physically.

- Embodied interaction – interaction experience should not only take into account material settings but also social interaction and how it is embedded in real space.
- Bodily movement – the user uses their own body to create movements and gestures which would transfer digital data.

They also state that the following is important to consider when prototyping tangible interaction:

- Sensuousness – how you input data, e.g. voice or movements, and when and how you get feedback, e.g. instant visual feedback.
- Graduality – whether interaction is weak or strong, e.g. just having two states, on and off, or having multiple input stages.
- Tightness – when and where do input and feedback occur, e.g. instant feedback in the same room versus feedback later in another room.
- Behaviour and adaptation – whether the behaviour of the object is predictable or confusing, and whether it is boring or makes the user angry.

Unfortunately, there are not many studies dealing with the use of tangible user interfaces for stroke rehabilitation. Nevertheless, it will provide designers with many opportunities and challenges. For example, tangible interaction gives the possibility to create portable devices which users can carry along with them. However, more research needs to be done on how to adjust tangible interaction for stroke survivors.

2.5 Vertical and horizontal prototyping

Vertical and horizontal prototyping can be used to implement interactive objects. Horizontal prototyping provides a wide range of features which lack in detail. In contrast, vertical prototyping shows fewer functions with more detail. These are illustrated in Figure 2.10. Horizontal prototyping focuses on user interaction rather than on functionalities, and are useful for understanding relationships and abilities of the system. Furthermore, it helps to estimate development cost and time. Vertical prototypes, on the other hand, are beneficial for exploring a complex function in detail.

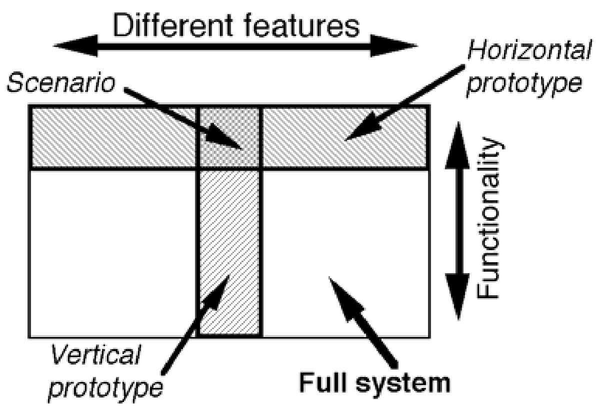

Figure 2.10 Vertical and horizontal prototyping [55]

3 Method

This chapter describes methods used in the project. It gives an overview of interaction design and research methods used in this project

3.1 Research methods

This project uses mainly qualitative research methods, although quantitative research methods are also used when necessary. As this paper draws a lot upon previous research, existing literature is studied to gain an understanding of different activities used for stroke rehabilitation and how interactive objects could be helpful. Previous implementations of interactive objects are thoroughly studied and any relevant points are used in the project.

Qualitative research methods are important to analyse human behaviour. Hence, rather than quantifying data, it is essential to answer questions such as who, what, when, where, why, how. This is essential when creating interactive objects for stroke survivors and determining how they should be designed to be easy to use as well as motivating. As it will be mentioned in Chapter 3.2, abled-bodied users are used to test the prototypes and data is collected using questionnaires to gain an understanding of how they perceive the interactive interface. Furthermore, literature on previous case studies and interviews are also studied to gain an understanding of how to design interactive objects for stroke rehabilitation.

Quantitative research expresses its data in numerical form. Since this project is mainly concerned with how people perceive the interactive objects developed, e.g. motivation, encouraging and fun, quantitative research is not that extensively used. However, it will be useful when conducting background research and can be used to support qualitative research.

This project relies mostly on empirical research as a lot of knowledge is obtained from experiments and observation, i.e. users who have tested the prototypes. However, exploratory research is also used to identify and define unclear questions.

3.2 Interaction design

The main focus of interaction design is on user experience. Cooper et al. [56, p. xxviii] say that interaction design "is concerned most significantly with satisfying the needs and desires of the people who will interact with a product or service." Hence, a product should not be confusing, ineffective or difficult to use, but rather the opposite. It should be enjoyable whilst helping the user in an effective and useful way.

People's strengths and weaknesses should be taken into account when designing a product to ensure as good of a user experience as possible. It is also important to consider who is going to use the product and how and where it is going to be used. However, different people value different things, and hence, finding a design that suits everybody is impossible. Thus, whilst designing, some compromises must be made in order to find a good outcome.

Interaction design consists of four repeated activities [57, pp. 329-330]:

1. Establishing requirements – determining target users and their needs.
2. Designing alternatives – creating ideas that would meet the requirements.
3. Prototyping – creating samples of the alternatives.
4. Evaluating – determining how well the alternatives match the requirements.

An iterative design approach is used in this project as it is both time- and cost-effective [58]. It consists of designing, prototyping and evaluation stages, as shown in Figure 3.1.

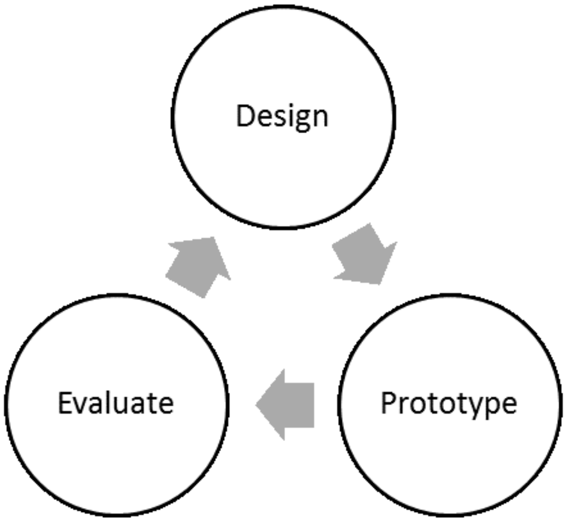

Figure 3.1 Iterative design process

User action is taken into account when designing an interactive object. Though stroke survivors will not be testing a prototype, previous knowledge obtained from user studies of the ActivABLES project is used for designing the prototypes. Therefore, even though it is not strictly a user-centred design process, the target users are always kept in mind.

A prototype will be constantly upgraded to meet the design requirements and employ results obtained at different stages of user testing. The fidelity of the prototype will increase during the development process, starting with more crude Lo-Fi prototypes gradually morphing into Hi-Fi prototypes. Low-fidelity prototypes are simple, take little resources to create and provide high-level feedback. However, their function is limited. As the project progresses, high-fidelity prototypes become more useful. Although they require more time and money, they have lots of detail and functionality. Since they are rather similar to the final product, they can be successfully used for user testing.

Testing can start when the first prototype is complete. It provides important information to go back upon whilst improving the design and prototype. However, it should also be kept in mind that too much tester involvement may also cause problems such that the final product becomes useless and ineffective for general purposes [57, p. 324]. Therefore, at least two abled-bodied people who do not know the details of the project will be involved in testing each prototype iteratively. During each testing session, they will complete a pre-test and a post-test questionnaire. The pre-test questionnaire is used to obtain background data of the participants. The post-test questionnaire obtains qualitative information about the testing experience and also uses the system usability scale [59]. The results will be taken into account to improve designs and upgrade prototypes. Although it requires some time to conduct the tests, using a testing-based iterative design process ensures that the final product is more likely to be effective and easy to use.

4 Proposed solution and structured design

This chapter describes the idea proposed for implementation as well as its advantages and disadvantages. Additionally, it gives an overview how structured design is used in this project.

4.1 Proposed solution

This project focuses on implementing a glove that would help stroke survivors with hand rehabilitation.

The idea is that a user would wear a glove with different sensors, such as flex and force sensors as well as an accelerometer. When the user moves their hand, fingers or squeezes something, the force applied could be determined using the sensors. Hence, it is a good way to give the user direct feedback which is an important part of rehabilitation.

This solution was chosen as around 85% of stroke survivors have loss of arm movement, many of whom claim that rehabilitation does not pay enough attention to arm rehabilitation [60]. Since arms are important for completing daily activities, arm-hand rehabilitation exercises and recovery of functions can be beneficial and is associated with improved quality of life [30, 60]. Hence, the glove could be used by a large range of people. Furthermore, the glove itself would not be too technical or intimidating, and should be suitable for non-technical people. Also, it would both be cognitively and physically easy to handle and suitable for use by stroke survivors.

The glove would not weigh too much and is relatively small in size and would therefore be comfortable to wear. The wires connected to the final product would be hidden so it will not be aesthetically unpleasing, and can be stored in a drawer or cupboard if needed.

The glove itself offers many opportunities. It can be implemented to do many tasks as it can be used for both rehabilitation as well as for controlling other devices, such as turning the TV on or off. Hence, this interactive object could potentially implement more functions than the glove discussed in Chapter 2.2. Additionally, the latter is rather expensive and mainly directed at healthcare institutions.

Thus, implementing a glove has many advantages. In addition to being easy to handle, it is also rather flexible and can be used to perform many exercises as well as help with different tasks. The ease of use is also a contributing factor that can encourage and motivate users.

4.2 Structured design of functions

In order to organise work and make finding errors as easy as possible, vertical and horizontal prototyping and structured design methods are used.

Horizontal prototyping is used to get an overview of the project's concept, while vertical prototyping is used to conduct the project in order to create a product which would be straightforward to use and would not confuse people with its wide range of functionalities. Furthermore, it is likely that having only one functionality would help to conduct user tests in a clear and easy way such that the results could be applied to designs without overcomplicating them.

Structured design gives an overview and helps to organise the project as it breaks the project down into several functions, showing the details inside them. In addition to making planning and working more efficient, it also helps to find errors as well as to distinguish important and unimportant parts.

Figure 4.1 shows a structured design for the vertical and horizontal prototyping of the project. Initially, three proposals were considered.

Firstly, the home automation function would involve using the glove to control devices at home. For example, by turning a hand either left of right, one can make the light in the room become either brighter or dimmer. This solution would mean that the users are encouraged to use the glove on a daily basis in order to achieve their goals, e.g. to turn the lights on and off. However, there are several shortcomings. Firstly, it might be difficult to integrate the glove with devices at home as each one comes with different functions which need to be considered. Secondly, performing exercises would be heavily dependent on the device and user's lifestyle. This means that the glove would be only be beneficial when it controls a device which the user frequently needs.

Secondly, the music playing function would use hand gestures in conjunction with computer software to create simple music. This function would be probably both encouraging and motivating. Being able to perform fun activities is very useful for rehabilitation and in turn helps people to achieve a better quality of life. However, as the glove needs to be easy to use, it cannot use too many or too complicated hand gestures. Hence, not a large number of different music sounds would be available. This in turn might become boring after some time, especially for those with less interest in music. Alternatively, those with previous musical talent may become frustrated as the glove would not enable them to play to the ability that they have been used to. Furthermore, some additional processing would be necessary to compensate against sounds which may not be pleasing to human ears.

Thirdly, the game-playing function would use the glove to control computer inputs, such as a mouse and keyboard, to play simple online games. There are a variety of games available for different age groups and tastes. Hence, it is likely that the user does not get bored as quickly as he or she has the ability to change a game whenever needed. As the number of computer instructions, such as a mouse click or pressing an arrow key is not vast, the product is likely to be easy to use. Additionally, it is a good way to encourage people to repeat exercises multiple times. However, using computers and playing online games might be intimidating for older people. Furthermore, each game has different instructions and may thus be difficult to learn. This function also assumes having a computer at home, which is not that uncommon anymore.

Considering the criteria and constraints listed in this and previous chapters, the home automation and music playing functions were discarded as they were too difficult to implement in the project's timeframe, as shown in Figure 4.1 (dashed lines). The game-playing function (solid line) is implemented as it can be well used for implementing the exercises outlined in Chapter 2.3.

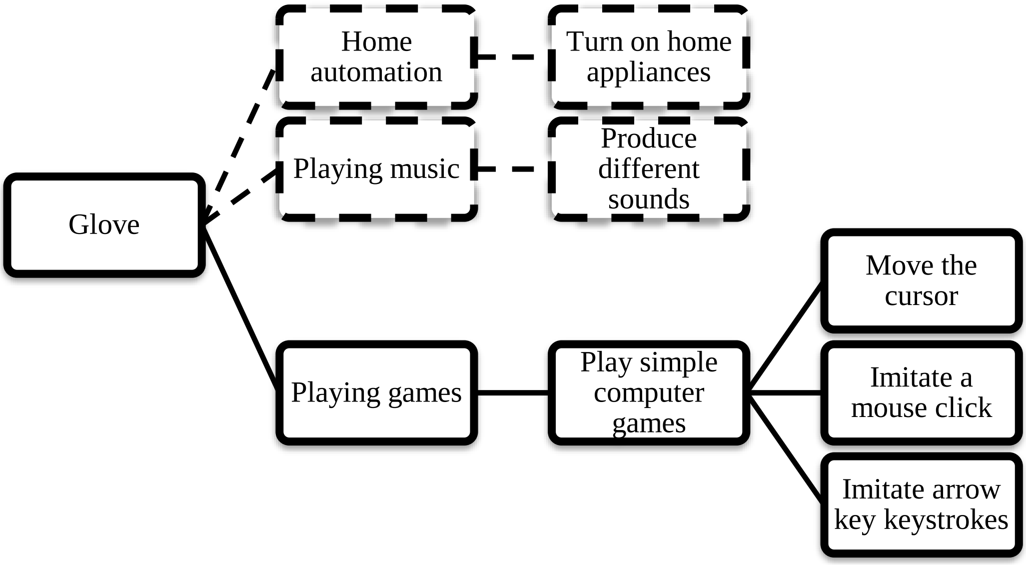

Figure 4.1 Structured design for the prototype (the dashed paths are branches which are cut/omitted, the solid path is the function to be implemented)

4.3 Exercise implementation

The object must implement active exercises, meaning that the user can move his or her hands without help from someone else. Furthermore, this project focuses on implementing an exercise that would be suitable for older people as they are the biggest group of stroke survivors. The average age of stroke survivors at the time of stroke is 70 years in men and 75 years in women [56]. However, there are also many children who have had a stroke. Hence, although not implemented in this project, the glove could be used to control toys. For example, the glove could act as a remote control for steering a toy car. The interactive object can be used to perform many hand rehabilitation exercises.

The game-playing function is great for implementing the exercises outlined in Chapter 2.3. Different exercise movements will be mapped to different keys on the computer. However, due to the scope of this project, and a limited number of exercises implemented, only the arrow keys, cursor movement, and mouse click will be implemented.

The wrist flexion/extension and supination/pronation exercises, shown in Figures 2.5 and 2.6, respectively, will be used to move the cursor on the screen. Lifting the wrist up moves the cursor upwards, left leftwards and so on. The whole arm could be used as well to imitate the movements. Furthermore, the sensitivity should be rather low in order to take into account imprecision and rapidness of hand movements.

The mouse click will be implemented using the finger flexion/extension and grip strengthening exercises, shown in Figures 2.7 and 2.9, respectively. By squeezing a ball in the hand, a mouse click will be registered. Furthermore, by measuring the force of the grip using the sensors, the user can get instant feedback of his/her progress.

Arrow keys will be implemented using simple finger movements as these controls seem to be a part of many online games. Furthermore, it gives a possibility to use four fingers simultaneously in a game and hence train them. The user has to tap a finger on a surface, as shown for the exercise in Figure 2.8. Each finger corresponds to one arrow key. By applying some pressure on a finger, an arrow key keystroke is registered.

Playing computer games which are fun and make use of the keystrokes and mouse movements mentioned above can be very beneficial for stroke rehabilitation. When the user is motivated and enjoys playing a game, he/she is likely to perform the exercises multiple times in a day. Although the small number of possible movements limits the number of games the user can play. Nevertheless, there are still many games which can be used in conjunction with the glove.

5 Designing, prototyping and testing

This chapter describes how the chosen idea is designed, built and tested as well as the materials used to create the interactive object. It also gives an overview of hardware and software implementations and of the testing phase.

5.1 Criteria and constraints

As mentioned in previous chapters, it is important to always have the end-user in mind. Hence, the following criteria needs to be considered whilst designing.

- Weight – should be light enough to wear for prolonged periods.
- Size – should not restrict the user's movements, and should be suitable for children and adults.
- Easy to use – clear and easy to follow instructions.
- Motivation – is it motivating and encouraging?
- Fun factor – the user should enjoy using the device.
- Aesthetics – should fit in in an average home.
- Technical appearance – the less wires and visible components, the better.
- Adjustability – the object should take into account the user's current abilities and his or her progress.

5.2 Materials

A number of materials were used to create low-fidelity and high-fidelity prototypes.

5.2.1 littleBits

littleBits was used for low-fidelity prototyping. It consists of small electronic building blocks, which can be snapped together with small magnets, such as LEDs, flex and pressure sensors. Although their functionality is rather basic and quite restricted, it can be used to create crude prototypes within minutes.

5.2.2 Arduino microcontrollers

The core of the interactive object is a microprocessor which controls how the device reacts to different inputs. The microprocessors used in this project are the Arduino UNO and the Arduino Leonardo. Arduino is great for easy and fast prototyping. It is also inexpensive and its various boards provide with lots of functionality. Furthermore, as both Arduino's software and hardware are open source, there is a large range of C libraries, wiring diagrams and extension shields available for different types of projects, which make implementation less time-consuming and cheaper.

The Arduino Leonardo, shown in Figure 5.1, was used for high-fidelity prototyping. It uses its microcontroller to both run code and for USB communication with the computer [61]. The Leonardo provides flexible communication with the computer due to being able to handle multiple protocols. For example, the Leonardo can use USB communications device class (USB CDC) and create a virtual serial port to the computer. Thus, the board can act as a HID (human interface device) mouse or keyboard, which is vital for the project. Although some other Arduino boards, such as the UNO, were considered as well, this functionality was the deciding factor why the Leonardo was chosen.

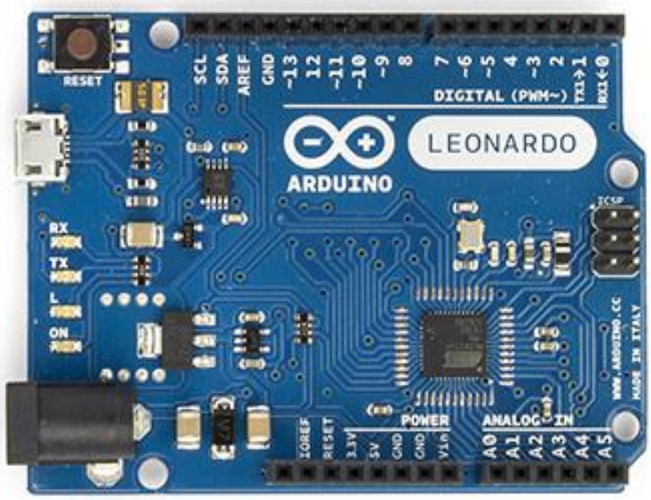

Figure 5.1 Arduino Leonardo [61]

The Leonardo's operating voltage is 5V and recommended input voltage 7-12V. It can be powered by a USB cable, but also with an AC-to-DC adapter or battery. Hence, it could be connected to the computer wirelessly and moved around. Additionally, since the project is heavily dependent on sensors, the number of input and output pins is also vital. The Arduino Leonardo has 20 digital I/O pins, of which seven can also be used as pulse-width modulated outputs and 12 as analogue input pins. Each I/O pin can provide 40 mA of current, and hence will be sufficient to run the sensors used in this project. The board is relatively small (68.6 mm x 53.3 mm) and light (20 g), and hence very suitable for this project.

5.2.3 LilyPad accelerometer

The ADXL335 three axes MEMS LilyPad accelerometer, shown in Figure 5.2, is used in this project to detect the position of the user's hand. It has a low noise and a low supply current of 350 µA [62], meaning it is suitable for use with the Arduino

Leonardo. The board's supply voltage is 5V and hence can be connected to the Arduino's 5V pin [63]. Furthermore, its maximum measurement range is ±3 g.

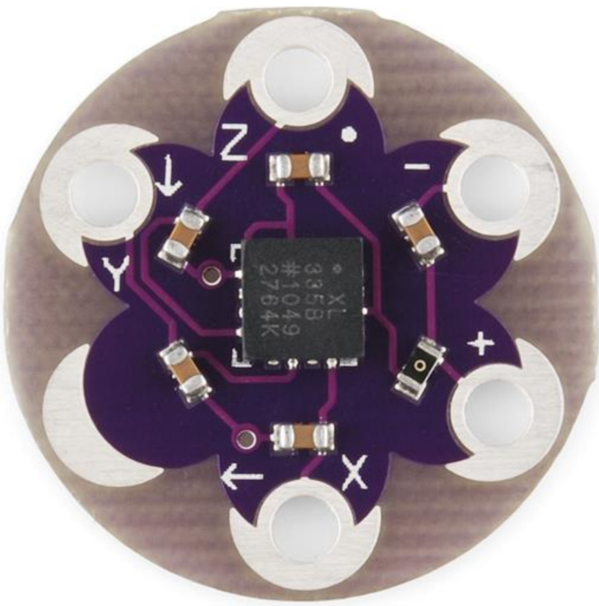

Figure 5.2 ADXL335 Accelerometer [64]

The LilyPad accelerometer is very suitable for usage in projects involving interactive objects. It has large connection pads to make it easy to sew into clothing and can also be washed [64]. Furthermore, it is rather small, 20 mm in diameter, and very light [64].

5.2.4 Sensors

The flex sensors by Spectra Symbol, shown in Figure 5.3, are used in the project to sense the bending of fingers. Its resistance when it is flat is $25k\Omega$, and increases as it is bent [65]. It is 2.2 inches long and hence suitable for sensing finger flexion.

Figure 5.3 Flex sensor [65]

The FSR 406 force sensing resistor by Interlink Electronics, shown in Figure 5.4, is used to sense the force of a squeeze in low-fidelity prototypes. When no force is applied, its resistance is very high (essentially an open circuit), but as the force increases, the resistance decreases drastically [66].

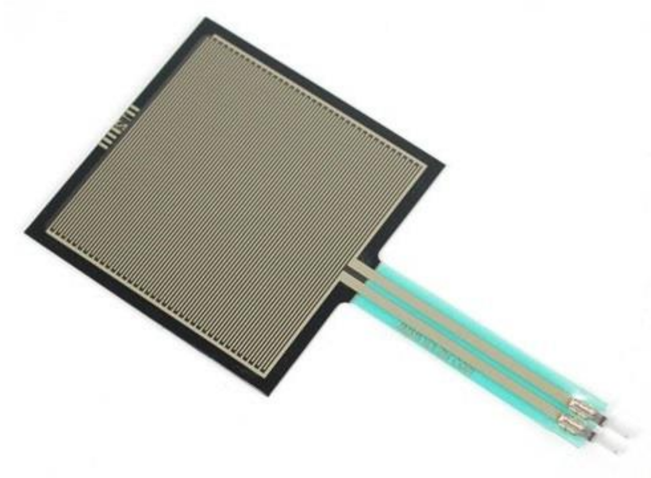

Figure 5.4 FSR 406 force sensitive resistor [66]

However, due to its thickness and sharp edges, it was determined that it might not be suitable for use in high-fidelity prototypes. The pressure sensitive sheet, also known as Velostat or Linqstat, shown in Figure 5.5, was used instead. Although it needed some preparatory work before it could be used, its thickness is only 0.2 mm and hence much more suitable for the project [67]. The material itself consists of a polymeric foil and carbon black, the latter making it electrically conductive. As with the FSR 406 described above, its resistance decreases as the force applied on it increases.

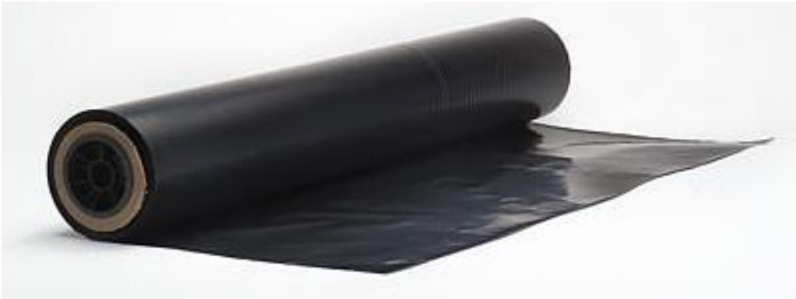

Figure 5.5 Pressure sensitive sheet [68]

5.2.5 Other materials

Furthermore, a normal glove, where all sensors were sewn into/attached to, was used. Two types of conductive thread were used in this project. The first one was silver-coated thread and was used for sewing the accelerometer into the glove. Its resistance is low over short distances and hence did not affect sensor measurements too much. The second thread had higher resistance and was used for creating force sensitive resistors using the pressure sensitive sheet.

5.3 Prototyping

5.3.1 Low-fidelity prototype

Low-fidelity (Lo-Fi) prototyping was used to gather quick feedback. It helps to visualise and test the function in a fast and cheap way, and to develop ideas before starting with high-fidelity prototyping.

littleBits was used to create the first prototype. Figure 5.6 shows a prototype which uses two flex sensors, a force sensitive resistor and LEDs. As the user interacts with sensors, the LEDs gradually turn on as more force is applied or the flex sensors are bent further.

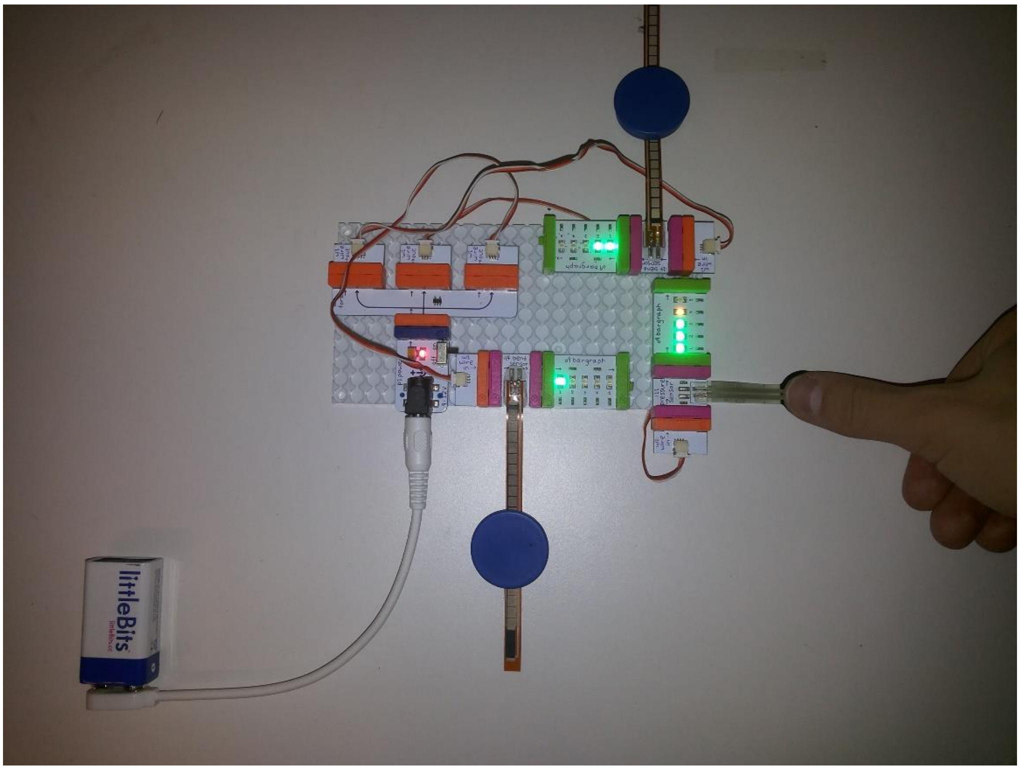

Figure 5.6 Lo-Fi prototyping with littleBits (the flex sensors are being bent by the two blue buttons and force is applied on the force sensitive resistor)

This prototype provided with some useful information. For example, it helped to determine which sensors should be used in the project. Furthermore, it gave an overview of the suitability of flex and pressure sensors. It was determined that the sensors are suitable for use in this project as they are very robust and easy to handle. Their simplicity makes them easy to use in conjunction with an Arduino to get quick measurements in a fast way. However, this prototype only concentrated on hardware and not on software.

While morphing towards a high-fidelity (Hi-Fi) prototype, another Lo-Fi prototype was created using the Arduino UNO, as shown in Figure 5.7. This step made use of both hardware and software capabilities of the board. This prototype was used to determine if the resistor values of the voltage dividers for the sensors are suitable, i.e. that the sensors are not too sensitive nor insensitive. `Serial()` function was used to display measurements on screen using the serial monitor. However, it was found that it is difficult to use the UNO as an HID mouse and keyboard, and hence the Leonardo was chosen instead, as explained in Chapter 5.2. The Flora microcontroller by Adafruit was also considered at this stage. It is a wearable electronic platform which can also be sewn and washed [69]. However, due to an insufficient number of input pins, its integration into this project would have been too complex.

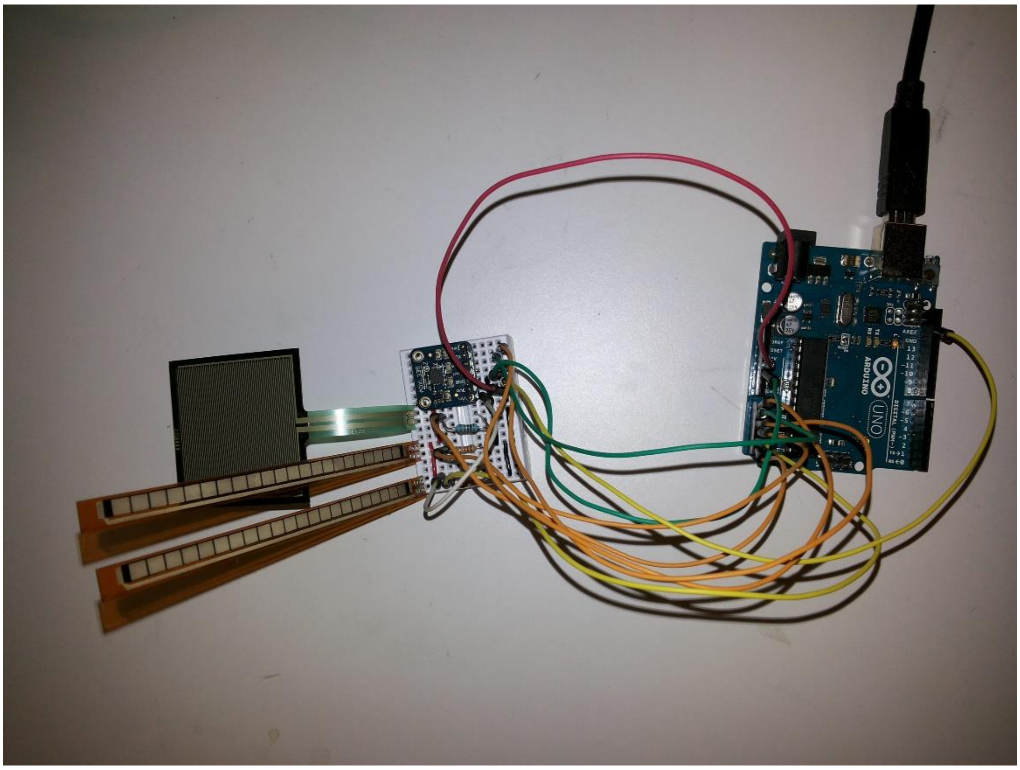

Figure 5.7 Lo-Fi prototyping with the Arduino UNO

5.3.2 High-fidelity prototype

While Lo-Fi prototypes are great for fast prototyping, they lack in detail and function. Hence, a high-fidelity (Hi-Fi) prototype was developed, which was more time-consuming, but had complete functionality and full interactivity.

The glove can be used to simulate three different computer functionalities.

1) Arrow key keystrokes
   The following algorithm performs an arrow key keystroke:
   - Check if fingers are not flexed.
   - Check if there is any pressure applied on any of the fingertips.
   - If the conditions above are satisfied, simulate pressing the arrow key corresponding to the fingertip.
2) Mouse click
   A mouse click was simulated by using the following algorithm:
   - Check if fingers are flexed.
   - Check if there is any pressure applied on the palm sensor for less than one second.
   - If the conditions above are satisfied at the same time, perform a mouse click.
3) Cursor movement

The cursor can be moved if the following conditions are satisfied:

- Check if fingers are flexed.
- Check if there is any pressure applied on the palm sensor for at least one second.
- If the conditions above are satisfied at the same time, use the accelerometer to measure the tilt of the hand, and move the cursor according to the data received.

Note that it follows similar steps to the mouse click implementation. However, a mouse click is only performed if the time of applying pressure on the palm sensor is less than one second. However, in order to move the cursor, the user has to keep applying force on the sensor as long as he/she wants to move the cursor.

The top and bottom views of the final design are shown in Figures 5.8 and 5.9, respectively.

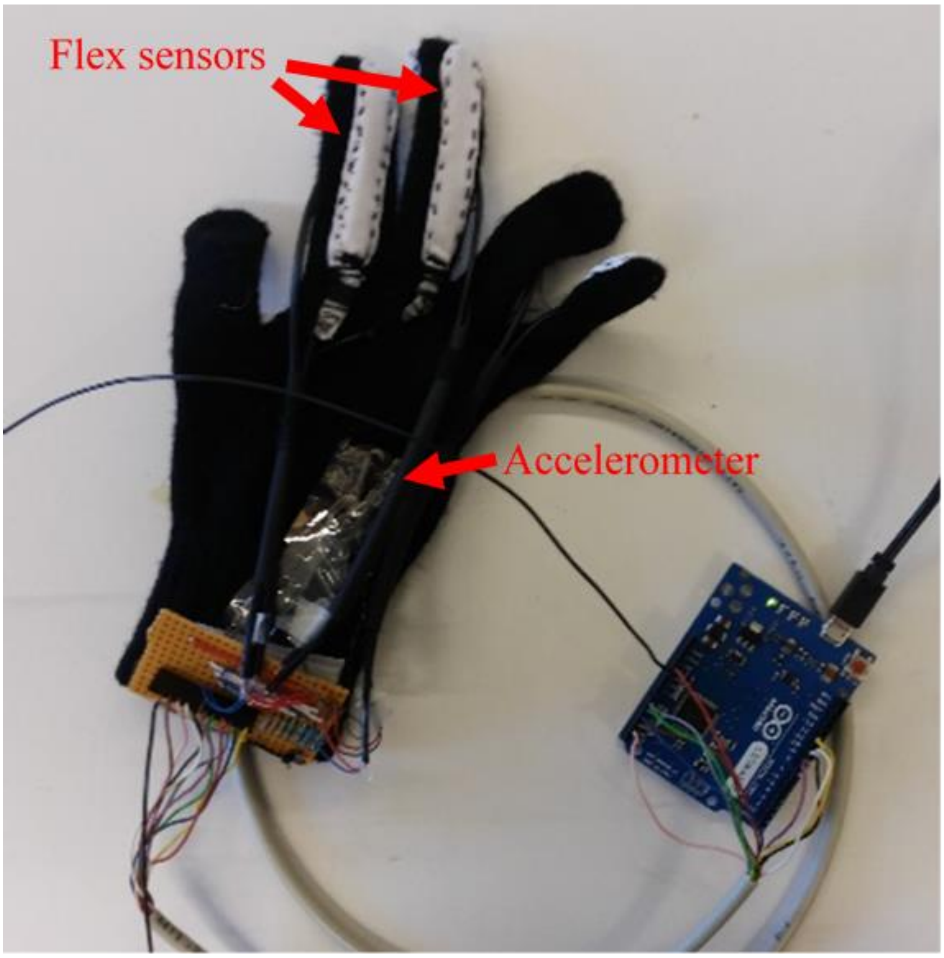

Figure 5.8 Top view of the glove

Figure 5.9 Bottom view of the glove

5.3.2.1 Hardware implementation

The circuit diagram of the project is shown in Appendix A.

In order to perform an arrow key keystroke, the following sensors are used: two flex sensors on the index and middle finger, and four force sensitive resistor (FSR) on the index, middle, ring and little fingers.

Voltage divider circuits, shown in Figure 5.10, were used for both flex and FSR sensors. The circuit used $V_{CC} = 5V$ input voltage, supplied by the Leonardo's 5V pin. Hence, the output V_{out} is given by:

$$V_{out} = \frac{R_2}{R_1 + R_2} V_{in} = \frac{R_2}{R_1 + R_2} * 5V. \quad \textbf{(1)}$$

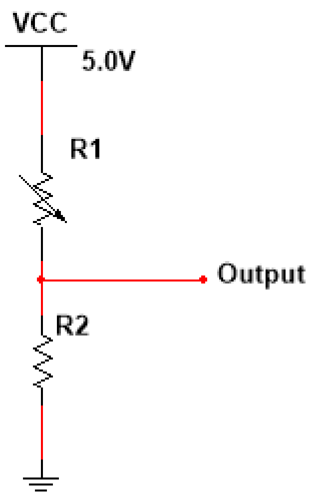

Figure 5.10 Voltage divider

In order to get a good analogue output reading from the circuit, the resistance range of the sensors (R1 in the figure) were measured. Measurements yielded that the flex sensors have the resistance of $R_1 = 25k\Omega$ when flat, and around $R_1 = 35k\Omega$ when a finger is bent. As the sensors are not extremely accurate, it was important that small changes do not influence the output much, but also that the output is sensitive to resistance changes. Using Equation (1), it can be shown that the voltage covers the largest range when

$$\frac{\partial}{\partial R_2}\left(\frac{R_2}{R_1 + R_2} - \frac{R_2}{R_1^* + R_2}\right) = 0, \quad \textbf{(2)}$$

where $R_1$and R_1^* are minimum and maximum resistances of the variable resistor and R_2 is the value of the fixed resistor to be found. Solving Equation (2) yields that maximum range is covered when

$$R_2 = \sqrt{R_1 R_1^*}, \qquad R_1 \neq R_1^*. \quad \textbf{(3)}$$

Thus, applying Equation (3), that the best value for $R_2 \approx 29.58k\Omega$. $R_2 = 27k\Omega$ was chosen as it was the closest resistor value available. It would have been possible to obtain an even closer resistance using serial and parallel resistor circuits. However, since it only makes the design more complicated, and this application is flexible on precision, it was decided to use a single resistor.

Using Equation (1) and the resistor values above, it can be calculated that the output voltage is approximately 2.60V when the sensor is flat and around 2.18V when a finger is bent. Since the Leonardo use 10-bit analogue-to-digital converter, i.e. analogue values are converted to digital values between $0 - 1023$, the corresponding output range will be between $446 - 531$. Hence, 500 is a good threshold value when determining if the sensor (finger) has been bent or not.

The force sensors have higher resistance when no pressure is applied and as more pressure is applied, its resistance decreases. The pressure sensitive sheet was used to handcraft the fingertip FSRs. Measurements showed that the average value of the FSRs was about $1.5k\Omega$ when no pressure was applied, and around 600Ω when moderate pressure was applied. Using Equation (3) yields that the output range is the greatest when $R_2 \approx 949\Omega$. $R_2 = 1k\Omega$ was chosen as it was the closest valued resistor available. Hence, when no force is applied, the output voltage $V_{out} = 2V$, corresponding to a digital value of 409, and with moderate force $V_{out} = 3.125V$, or otherwise a digital value of 639. Again, the threshold value of 500 can be used to determine whether there is any pressure on the fingertip or not.

The mouse click function uses the following sensors: two flex sensors on the index and middle finger, and an FSR in the palm. The flex sensors are the same as those used for the arrow key keystroke function. The FSR measures the pressure in the palm, and acts essentially in the same way as the FSRs on the fingertips. It was handcrafted using the pressure sensitive sheet and conductive thread. It is also worth mentioning that a normal hand-size ball was used to apply force on the palm sensor by squeezing the palm, as the sensor could not be conveniently reached by just fingertips.

The resistance of the FSR in the palm with no force applied is around $23k\Omega$, and with force about $1.5k\Omega$. Using Equation (3) gives that $R_2 \approx 5.87k\Omega$. The closest value available was $R_2 = 5.6k\Omega$. Using these values, $V_{out} \approx 0.98V$ when there is no force on the sensor, and $V_{out} \approx 3.94V$ when force is applied. This corresponds to digital values of 200 and 807, respectively. Hence, again, 500 is a good threshold value for detecting force on the sensor as it lies roughly in the middle.

The cursor movement function uses the flex sensors, the FSR in the palm, and the accelerometer. This project only uses the x and y axes of the accelerometer since the cursor movement itself is two dimensional.

When the glove is flat on a surface, it only experiences gravitational acceleration in z direction, i.e. $x = y = 0\ g = 0\ m/s^2$. It was measured that the output of x and y axes in that case was about 2.47V. When the glove is turned to the right or upwards, the gravity of $1\ g$ acts in x and y directions, respectively, and when turned to the left or downwards, force of $-1\ g$ acts in x and y directions, respectively. It was measured that the output was approximately 1.91V when $F = -1\ g$ and about 2.98V when $F =$

1 g. The corresponding digital values are 505 for 2.47V, 390 for 1.91V and 610 for 2.98V.

5.3.2.2 Software implementation

The code that was used to programme the board is shown in Appendix B.

The code starts by importing the `Keyboard` and `Mouse` libraries, as shown in Figure 5.11, which are used to control the mouse and the keyboard of the computer. After that a number of variables are defined, such as input pins and different threshold values.

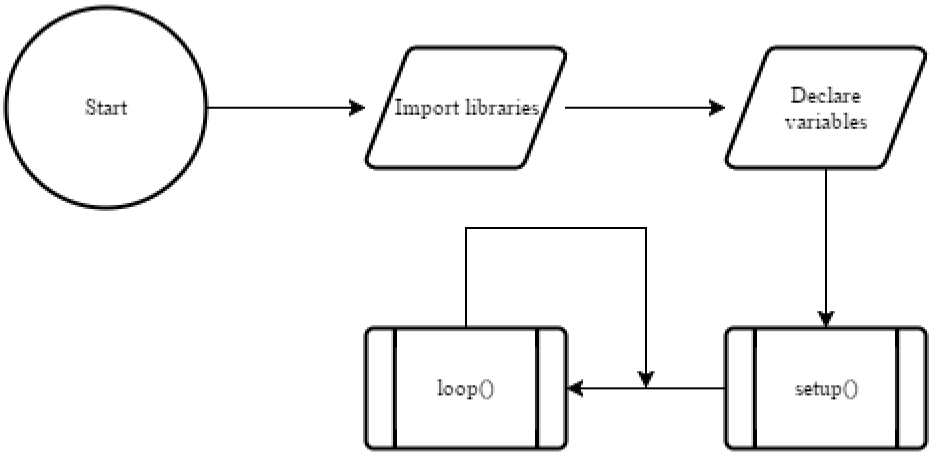

Figure 5.11 Flowchart of the program

The `setup()` function of the code is run only once, when the board is powered up. It defines the pins used as input pins and also calls two functions, `Mouse.begin()` and `Keyboard.begin()`, as shown in Figure 5.12. They start emulating the mouse and the keyboard, respectively.

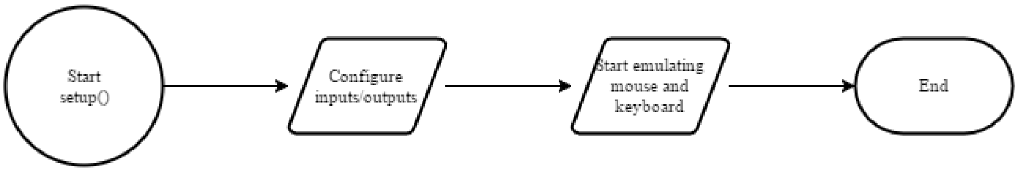

Figure 5.12 Flowchart of the `setup()` function

The `loop()` function is the central part of the code. It is a continuous function and runs as long as the board is powered. The flowchart of the loop function is shown in Figure 5.13.

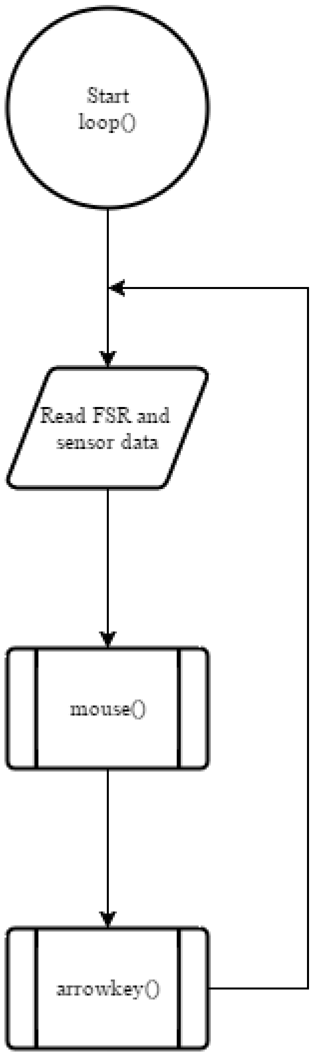

Figure 5.13 Flowchart of the `loop()` function

The function reads the output values of the flex and FSR sensors using the built-in `analogRead()` function, which returns a value between `0` and `1023`. These values are then used in two other functions, `mouse()` and `arrowkey()`, which are called inside the `loop()` function.

The `mouse()` function is shown in Figure 5.14. Its inputs are the integer values of the flex sensors and FSR in the palm which were obtained in the `loop()` function. The function starts by recording the start time of the function using the `millis()` function, which returns the time in milliseconds since the program began running. It also sets the current iteration time to zero, although technically no loop iterations have happened at this point. It then determines if the fingers are bent and if there is any pressure applied on the sensor in the palm. Both of these are done by comparing the output values of the sensors with the threshold values initialised in the declaration section of the program. If the conditions are not satisfied, the function checks if the time difference between the start time and the time of the last iteration is less than a threshold (1 second in the final implementation). If yes, the function uses the `Mouse.click()` function which simulates a left button click and then ends. Otherwise, the function ends instantly. However, if the sensor conditions are satisfied, the time of the current iteration is saved. If the time difference between the start time and the time of the current iteration is above the threshold, the `mouse_distance()` function is called which returns a scaled value of the accelerometer readings. These scaled values are then used to move the cursor on screen using the `Mouse.move()` function relative to the cursor's current location. After that, the sensor values are updated. However, if the time is less than the period, this is done straight away. The function then checks again if the sensors' conditions are satisfied and continues as described above.

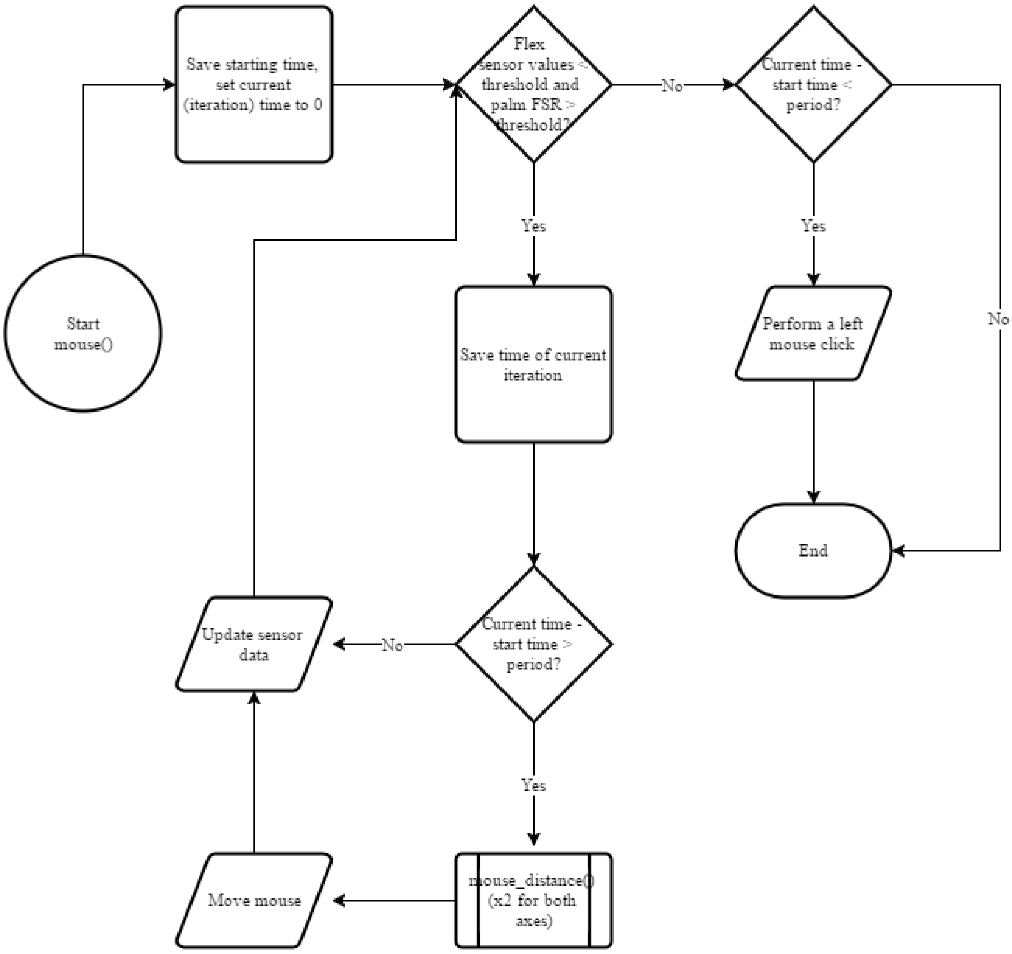

Figure 5.14 Flowchart of the `mouse()` function

Figure 5.15 shows the flowchart of the `mouse_distance()` function. Its only input is the number of the accelerometer's pin. It starts by measuring the output of an accelerometer's axis. Using the `map()` function, this value is then scaled down to a number between the maximum and minimum movements desired which are defined in the global variables' declaration section. In this implementation, values of the x-axis have been inverted to ensure that the cursor is moving in the right direction. If the value is above the threshold, defined at the same place, the function returns the value. Otherwise, the value of zero is returned. This helps to ensure that only hand movements, which are significant enough, result in cursor movements.

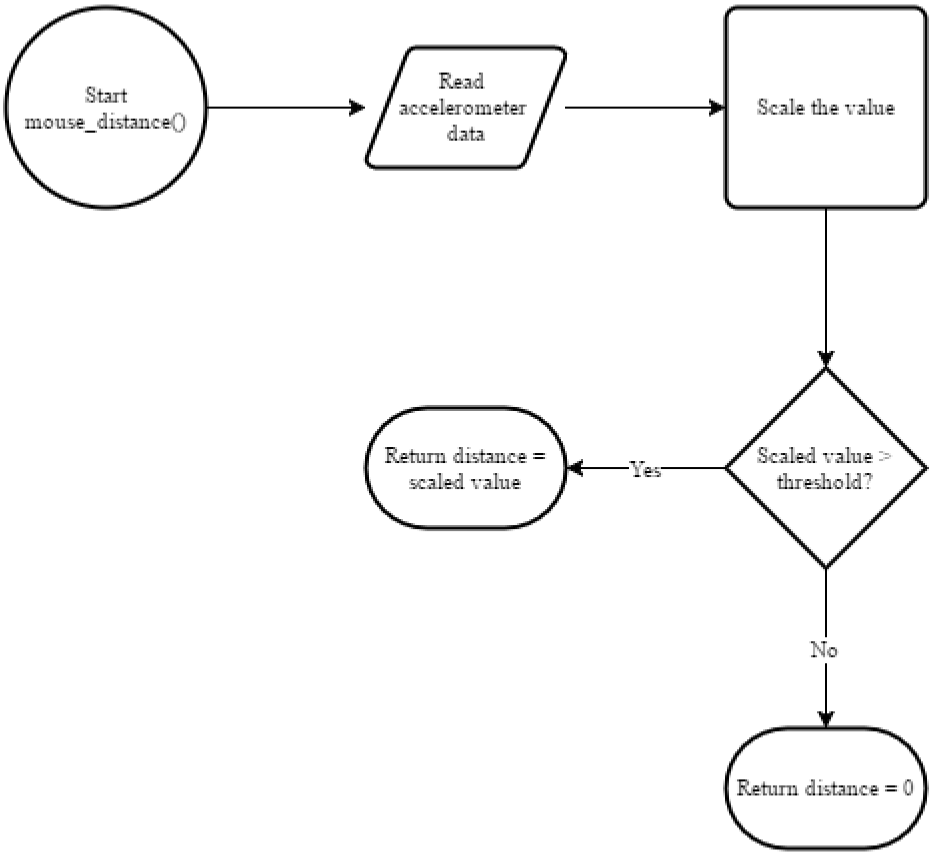

Figure 5.15 Flowchart of the `mouse_distance()` function

The flowchart of the `arrowkey()` function is shown in Figure 5.16. As mentioned above, this function is called in the `loop()` function and is used for simulating arrow key keystrokes. The function starts by checking if the flex sensors' output values are above the threshold, i.e. the flex sensors are not bent. If it is not satisfied, the function ends. Otherwise, the function starts to check if the output values of the FSRs are above the threshold value, i.e. force is applied on a sensor. If yes, the corresponding arrow key keystroke is simulated and the function continues with checking the other sensors. Otherwise, the checks are done straight away. If all the checks have been completed, the function ends.

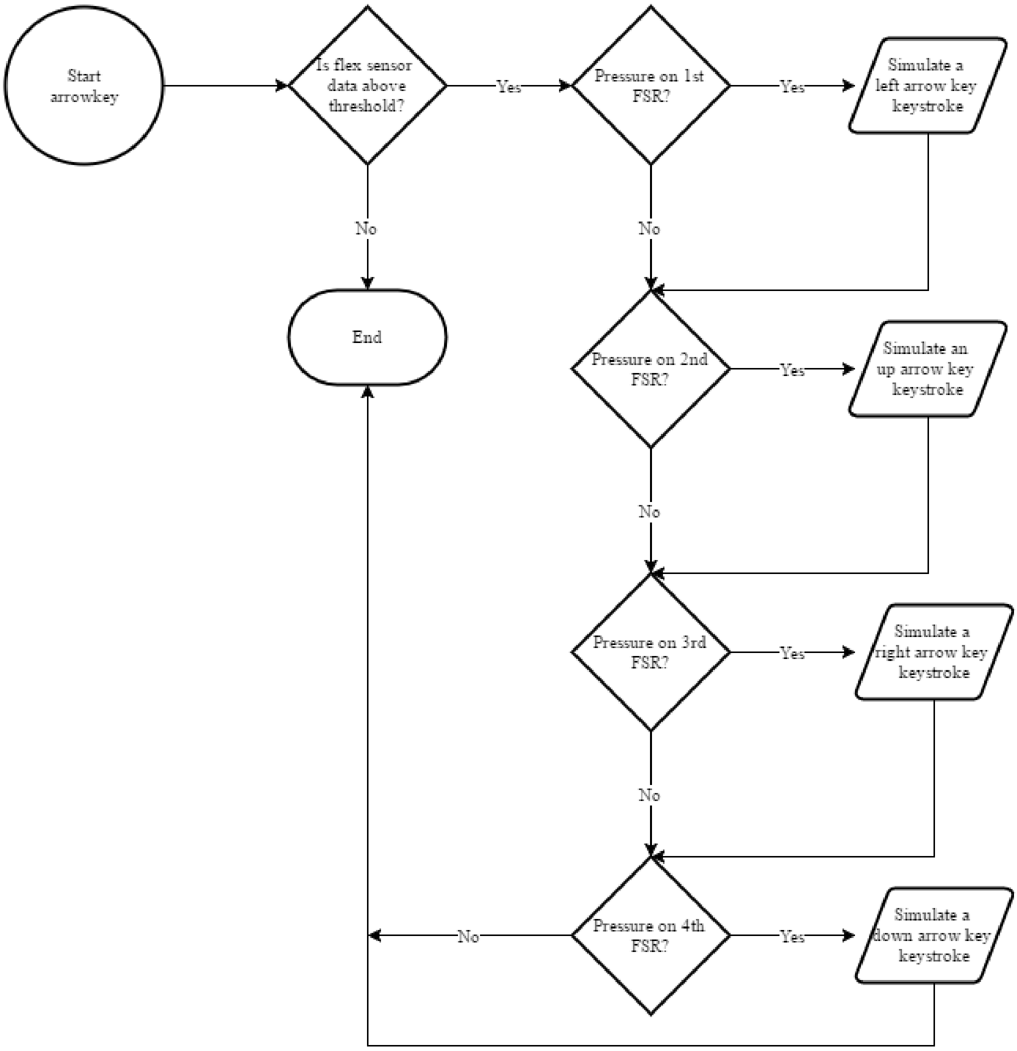

Figure 5.16 Flowchart of the `arrowkey()` function

5.4 Testing

The interactive object was tested to get feedback about what is good and what could be improved. This is also the basis of the iterative design process, discussed in Chapter 3.2. The tests were also accompanied by a questionnaire that the testers filled in, shown in Appendix C.

Firstly, a tester was presented with the pre-test questionnaire, which asked them about their background, cognitive and motor abilities, and how often and for what purpose they use computers. Then a test was conducted where the user tested different functionalities of the glove. Finally, the tester filled in the post-test questionnaire which used the system usability scale (SUS). The tester was presented with multiple questions which asked to assess his/her experience using the glove. He/she could also say what they liked about the product and what could be improved.

Four people took part in the testing who were not aware of the details of the project. All of them were in their 20s and indicated no cognitive or motor impairments in their responses. Three of the users were right-handed and one left-handed. Although the glove was designed for right-handed people, he was willing to use his right hand and was successfully able to interact with the glove. All of them are also frequently using computers for different activities and hence had no difficulty understanding the functions of the glove.

Firstly, the testers were given a short summary about the project and the glove. After learning about different functions of the glove and filling in the pre-test questionnaire, they could go online and pick a game which they liked and could be played using the functions of the glove. For example, one tester successfully played a game called Flappy Bird which used only mouse clicks as its input to guide a bird through rows of pipes. Furthermore, the testers also tried to control the computer using the glove, e.g. opening different programs and surfing the web.

In order to follow the iterative design process, after the first two tests, the glove was adapted to the feedback received from the testers. A few recommendations were suggested. Firstly, in the initial Hi-Fi design, the sensors were just attached to the glove by securing them in place with thread. However, during testing both testers experienced that sensors got stuck in it when they were moved, especially the flex sensors. As a solution they were covered by a fabric which was then sewn into the glove, as can be seen from Figures 5.8 and 5.9. The fabric is stretchable and hence very suitable for this application, where the shape of it needs to change as a result of bending. Secondly, there were some complications using the glove, as its response was either too sensitive or insensitive. The resistor values were recalculated, replaced and the threshold values in the code changed according to the values mentioned in Chapter 5.3.2.1. Lastly, both testers also recommended to sew the cables into the glove as they were too loose at this point of testing.

After these tests, the design was modified to take into account the recommendations. After that, two new testers tested the glove and filled in the post-test questionnaire with their feedback. They reported a problem with using the glove to move the cursor, something which had been already mentioned during the first two tests. Although it was better this time, the cursor movement could not be used to play games due to its slow and a bit imprecise movements. Furthermore, during one testing the tester revealed that the ball used in the testing was too stiff as the hand became tired quickly. A softer ball was used instead which was easier to use for longer periods. However, it should be noted that extremely soft balls are not recommended as they might not apply enough force on the palm sensor. Hence, a mouse click might not be registered, unless changing the threshold values. Lastly, during all tests, people were afraid of damaging the sensors, especially the flex sensors, when putting on or taking off the glove. Hence, it was recommended to do it slowly in a way that the sensors are not bent too much. Unfortunately, it was not possible to change this due to inevitable characteristics of the sensors.

Although due to the low number of testers no solid conclusions can be made, all testers said that they enjoyed using the glove and would also do so in the future. They also said that the glove was easy to use and its low number of functions did not require much learning. Apart from having a few problems with using the glove to move the cursor, they said that using the glove does not require much help from others. The feedback also revealed that although users with different hand sizes could use the glove itself, its material might not be the best for longer periods of use as the material is rather thick. Furthermore, although the testers did not think that the glove itself was aesthetically unpleasing, they said that it would look nicer if the cables were less visible. Additionally, they also thought that having more functions would be beneficial.

All the users said that they believe the glove could be used to motivate stroke rehabilitees. They suggested that in addition to playing games, it could be used to perform other activities such as browsing the Internet. However, their main motivation was that they enjoyed using the glove and when playing games, they performed different hand movements for multiple times by concentrating on the game rather than on the hand movements itself. Hence, it would be likely the case with many other people. Furthermore, it was mentioned that using the glove to play games is also competitive and hence motivating. For example, the testers wanted to beat their own and other testers' high scores by playing games over and over again. Hence, this might also be encouraging for competitive stroke rehabilitees.

In conclusion, the testers thought that the glove was easy to use and could be beneficial for exercising hand muscles, for example those involved in gripping. Although there are things which could be improved, it was generally functioning well.

6 Conclusions

This chapter includes the main findings of the project. It also analyses limitations of the final design which could be improved upon and also provides recommendations for future work.

6.1 Discussion and conclusions

Stroke as a disease affects millions of people around the world. Although it is mainly prevalent in developed countries, the number of stroke survivors is also increasing in developing countries. Those who survive a stroke have generally lost some of their ability to perform activities of daily life. Hence, it is highly recommended that in addition to rehabilitation with a physician the stroke survivor would exercise at home as well. However, many studies have shown that repeating the same exercises every day without seeing any improvement may be very demotivating as well as discouraging. Thus, many people give up rehabilitation completely due to their lack of motivation.

A solution is to create interactive objects which would take into account a person's current abilities as well as interests. Several studies have shown that those using interactive objects tend to be more motivated and show better results than those relying on conventional methods. However, the options are rather limited and some products are directed more on healthcare institutions rather than on individual people. Thus, it is important to develop interactive objects which would not be expensive, but would be motivating and would cater for a wide range of interests. It is also important to take into account other factors such as how easy is the device to use and how well does it fit in with the aesthetics at home. Additionally, the user should get some feedback, for example regarding his/her progress.

This thesis was concerned with how interactive objects can be beneficial for mobility training and stroke rehabilitation. A number of ideas were proposed and their advantages and disadvantages analysed. It was decided that using a glove, which could be used to control a computer's mouse and keyboard, could be a good approach as it can be used to play online games and is suitable for implementation in the short timeframe of the project.

After studying previous papers, it was determined that the final product should be easy to use, lightweight, small in size, aesthetically pleasing, and most importantly fun and motivating. Furthermore, the glove also caters for a wide range of stroke survivors, not for just a particular age group.

The glove is used to perform different hand and finger exercises. For example, in order to move the cursor, the wrist pronation and supination exercise must be performed. Additionally, a grip strengthening exercise is used to perform a mouse click while finger lifting is used to simulate arrow key keystrokes.

The Arduino Leonardo microcontroller was used as it can be used as a human interface device to emulate a mouse and keyboard. Furthermore, it is small in size, light and can be used for many different purposes. Both Arduino’s software and hardware are open sources and hence the resources are vast. In addition to the board, an accelerometer, flex sensors and force sensitive resistors were used to determine hand and finger movements. Thus, the production costs of the glove are much cheaper compared to other alternatives on the market. This in turn means that the product could be directed at individuals rather than at healthcare institutions.

An iterative design process was used to keep the end user in mind. This means that after designing and prototyping, tests were done and the results were used to change the design so that it would be more comfortable to use. The system usability scale was used to get feedback about the object in a simple, fast and inexpensive way. Although stroke survivors were not involved in the testing phase, it nevertheless gave useful feedback which could be used to improve general functionality. Four testers tested the glove and all of them reported that the glove was easy and enjoyable to use and could possibly be motivating for those who have suffered from a stroke and might need help with recovering abilities of their hand. They claimed that the main advantage of using the glove is that the concentration is on playing games and interacting with the glove rather than performing exercises.

As the technology-assisted rehabilitation is becoming more popular, it is important to have discussions with the target group to determine their expectations as well as concerns. Furthermore, it is also important that stroke survivors would be confident in using the device. This could be solved by splitting complex tasks down into simpler ones, for example, which is used by the technology-supported task-orientated arm training method. Additionally, it is also important to create tasks which have a meaning, i.e. the rehabilitee needs to do the same task in his/her daily life. However, there should be a balance between rehabilitation and what the user likes to do to keep him/her motivated. Furthermore, too much exercising might be discouraging as well. Thus, involving stroke patients is vital in order to create devices which would be both motivational as well as beneficial.

In conclusion, interactive objects can be very supportive when it comes to stroke rehabilitation. In addition to helping the users to perform exercises in a correct way, it can also be motivating and encouraging. The number of solutions on the market is constantly growing and the research focus on the topic is becoming more important. It is likely that in the future rehabilitation would involve interactive objects which would take into account the user’s interests and abilities and hence would help with performing activities of daily life.

6.2 Future work

Due to the scope of the project, limitations of the final product are inevitable. Hence, the following could be improved to make the glove even more usable.

Firstly, the current prototype lacked adaptability by not having an option to modify threshold values of the functions without re-programming the microprocessor. Hence, a functionality, which could determine the user's abilities such as grip strength, would be advantageous so the same product could be used by different people without any programming intervention. Furthermore, it would also be good if people could track their own performance, for example by collecting data which could later be used to create graphs.

Since some sensors of the glove were handcrafted, they were not as precise as those manufactured by a specialised company. Hence, the sensors in the current design could be swapped. Although precision is not extremely important in this application, it might ensure better overall functionality of the glove. Furthermore, the cursor movement function and sensitiveness needs to be improved to make it more accurate and easier to use.

Although the Arduino Leonardo board is great for prototyping, its size and functionalities are not the most suitable for use in the final product. Instead, a microcontroller chip should be used which might result in more complex software and hardware implementations, but greatly reduces the size of the final product.

Another improvement would be to emulate more mouse and keyboard functions. Currently, only the mouse click, cursor movement and arrow key functions are available. However, with addition of more sensors, it would also be possible to use other keys on the keyboard. Furthermore, it would be an advantage if the glove could be used to control other devices, such as the TV, as well.

It is also important to create online games which would be directed at stroke survivors and would allow them to use their hands for various exercises. A large database of games would potentially have something for everybody, for example games for different age groups or people with different interests.

The aesthetics of the glove could also be improved as the current design did not make much effort to hide the cables. Furthermore, creating a wireless version of the glove would also decrease the number of cables as well as would provide extra freedom. Additionally, the glove could be made of a material which might be more user-friendly when using for extended periods of time, for example not as thick. Furthermore, the sensors should be secured in a way that they could not be damaged easily, for example when putting on or taking off the glove, which the testers were worried about when testing the high-fidelity prototypes.

The final prototype was made for the use of the right hand. However, as the weaker hand of stroke survivors is dependent on the hemisphere of the brain where the stroke occurred, there are also many people who need rehabilitation with their left hand. Hence, a similar product, but for the left hand, should also be created.

Finally, the testing did not involve any stroke survivors as in previous ActivABLES projects. Hence, in the future it would be very advantageous to involve them in every stage of the project, so the final product would be designed according to actual needs.

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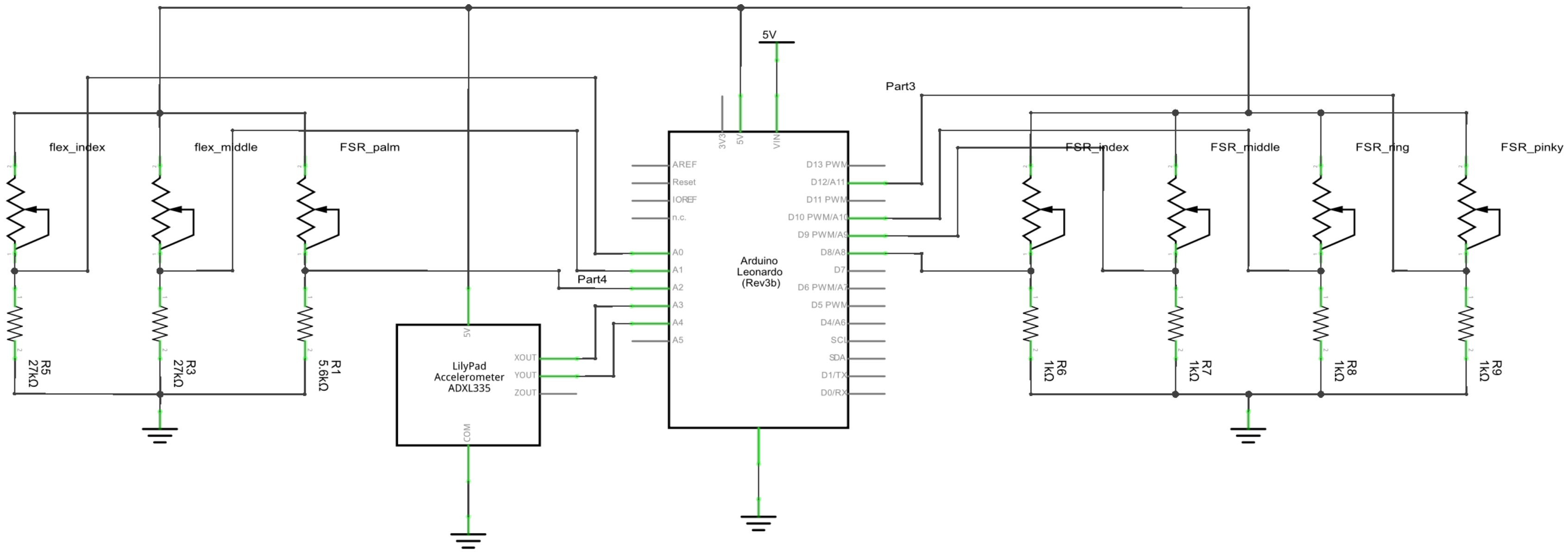
Appendix A: Schematic



Appendix B: Code

```
/*
 * Title: Glove
 * Author: Mihkel Hiob
 * Date: Jun 2016
 * Code version: 2.3
 */

#include <Keyboard.h>
#include <Mouse.h>

// Pin definitions
const int flex_index = A0;  // Index finger, flex sensor
const int flex_middle = A1; // Middle finger, flex sensor
const int fsr_palm = A2;    // Palm, pressure sensor
const int acc_x = A3;       // Accelerometer, x-axis
const int acc_y = A4;       // Accelerometer, y-axis
const int fsr_index = A8;   // Index finger, pressure sensor
const int fsr_middle = A9;  // Middle finger, pressure sensor
const int fsr_ring = A10;   // Ring finger, pressure sensor
const int fsr_pinky = A11;  // Pinky finger, pressure sensor

// Threshold values
const int click_thres = 500;      // Mouse click threshold
const int flex_thres = 500;       // Flex sensors threshold
const int keystroke_thres = 500;  // Keystroke threshold
(finger FSRs)

const long period = 1000;   // Duration before the palm
pressure sensor must be activated in order to move the cursor
(in ms)

// Accelerometer and cursor movement values
const int max_move = 20;    // Max movement of cursor (in
pixels)
const int move_thres = max_move/5;  // Minimum movement (in
pixels)
const int minimum = 390;      // Min value of the accelerometer
reading
const int maximum = 610;    // Max value of the accelerometer
reading
```

```
void setup() {
  pinMode(flex_index, INPUT);
  pinMode(flex_middle, INPUT);
  pinMode(fsr_palm, INPUT);
  pinMode(acc_x, INPUT);
  pinMode(acc_y, INPUT);
  pinMode(fsr_index, INPUT);
  pinMode(fsr_middle, INPUT);
  pinMode(fsr_ring, INPUT);
  pinMode(fsr_pinky, INPUT);

  Mouse.begin();    // Initialise mouse control
  Keyboard.begin(); // Initialise keyboard control

}

void loop() {
  int fsr_palm_val; // Palm sensor's value
  int flex_index_val, flex_middle_val;  // Flex sensors' values
  int fsr_index_val, fsr_middle_val, fsr_ring_val,
fsr_pinky_val; // Finger FSR sensors' values

  // Sensor measurements
  fsr_palm_val = analogRead(fsr_palm);
  flex_index_val = analogRead(flex_index);
  flex_middle_val = analogRead(flex_middle);
  fsr_index_val = analogRead(fsr_index);
  fsr_middle_val = analogRead(fsr_middle);
  fsr_ring_val = analogRead(fsr_ring);
  fsr_pinky_val= analogRead(fsr_pinky);

  mouse(fsr_palm_val, flex_index_val, flex_middle_val);  //
Mouse functions
  arrowkey(fsr_index_val, fsr_middle_val, fsr_ring_val,
fsr_pinky_val, flex_index_val, flex_middle_val);  // Arrow key
keystroke function

}

/*
 * Simulates arrow key keystrokes if the flex sensors are not
 * bent and the pressure on a finger FSR is at least the
 * threshold value.
 *
 * fsr1_val, fsr2_val, fsr3_val, fsr4_val: measured values of
the finger pressure sensors
 * flex1_val, flex2_val: measured values of the flex sensors
 */
void arrowkey(int fsr1_val, int fsr2_val, int fsr3_val, int
fsr4_val, int flex1_val, int flex2_val) {
  if ((flex1_val > flex_thres) && (flex2_val > flex_thres)) {
```

```
    if (fsr1_val >= keystroke_thres) {
      Keyboard.write(KEY_LEFT_ARROW);
    }

    if (fsr2_val >= keystroke_thres) {
      Keyboard.write(KEY_UP_ARROW);
    }

    if (fsr3_val >= keystroke_thres) {
      Keyboard.write(KEY_RIGHT_ARROW);
    }

    if (fsr4_val >= keystroke_thres) {
      Keyboard.write(KEY_DOWN_ARROW);
    }

    delay(100);
  }
}

/*
 * Performs a mouse click if the flex sensors are bent and the
 * pressure on the palm has been at least the threshold value
 * for less than the period. If at least the period, moves the
 * cursor.
 *
 * fsr_val: measured value of the palm sensor
 * flex1_val, flex2_val: measured values of the flex sensors
 */
void mouse(int fsr_val, int flex1_val, int flex2_val) {
  unsigned long starttime = millis(); // Register the starting
time of the function
  long previoustime = 0; // Last registered time
  int xDist, yDist;

  while ((flex1_val <= flex_thres) && (flex2_val <= flex_thres)
&& (fsr_val >= click_thres)) {
    previoustime = millis();

    // Enable mouse movement
    if (previoustime - starttime >= period) {
      xDist = mouse_distance(acc_x);
      yDist = mouse_distance(acc_y);
      Mouse.move(xDist, yDist, 0);  // Move cursor
      delay(10);
    }

    // Update the values
    fsr_val = analogRead(fsr_palm);
    flex1_val = analogRead(flex_index);
    flex2_val = analogRead(flex_middle);
  }
```

```
  // The pressure was applied for less than 1 second (period)
  if ((previoustime - starttime < period) && (previoustime >
0)) {
    Mouse.click(MOUSE_LEFT);
  }
}

/*
 * Reads the value from the accelerometer and determines
 * how much to move the cursor and returns this distance.
 *
 * pin_number: measurement pin
 */
int mouse_distance(int pin_number) {
  int distance = 0;
  int value = analogRead(pin_number);
  int scaled_value = map(value, minimum, maximum, -max_move,
max_move);

  // Check if the scaled value is above the threshold
  if (abs(scaled_value) >= move_thres) {
    distance = scaled_value;
  }

  // Invert x-axis values to move the cursor in correct
direction
  if (pin_number == acc_x) {
    distance = -distance;
  }

  return distance;
}
```

Appendix C: Questionnaire

Pre-test questionnaire

A. Basic information

1. Gender: ☐ Male ☐ Female
2. Age _____ years

B. Cognitive and motor abilities

1. How would you rate your cognitive and motor abilities?
   ☐ Very good
   ☐ Good
   ☐ Moderate
   ☐ Poor
   ☐ Severely affected
2. Do you have any kind of cognitive or motor impairments? If yes, please provide with some details. ☐ Yes ☐ No
   ____
   ____
   ____
3. Dominant hand: ☐ Left ☐ Right

C. Experience with computers

1. Do you own a computer? ☐ Yes ☐ No
2. If yes, how long have you used a computer?
   ☐ Less than a year
   ☐ 1-3 years
   ☐ More than 3 years
3. On average, how many times do you use a computer in a week for the following activities?

	0	1-5	6-10	More than 10
Browsing the Internet				
Writing				
Playing games				
Other (please specify)				

Post-test questionnaire (System usability scale adapted from [59]):

A. System usability scale

1 – strongly disagree 5 – strongly agree

	1	2	3	4	5
1. I think that I would like to use this glove frequently.	□	□	□	□	□
2. I found the glove unnecessarily complex.	□	□	□	□	□
3. I thought the glove was easy to use.	□	□	□	□	□
4. I think that I would need the support of a technical person to be able to use this glove.	□	□	□	□	□
5. I found the various functions in this glove were well integrated.	□	□	□	□	□
6. I thought there was too much inconsistency in this glove.	□	□	□	□	□
7. I would imagine that most people would learn to use this glove very quickly.	□	□	□	□	□
8. I found the glove very cumbersome to use.	□	□	□	□	□
9. I felt very confident using the glove.	□	□	□	□	□
10. I needed to learn a lot of things before I could get going with this glove.	□	□	□	□	□

B. Feedback

What did you like about using the glove?

____

____

____

What do you think could be improved?

____

____

____

Do you think that the glove is fun to use and could potentially motivate those who have suffered from a stroke? Please explain your answer. □ Yes □ No

____

____

____