STITCHED STRAIN SENSORS

SUPPORTING AT-HOME REHABILITATION EXERCISES

MASTER THESIS
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STITCHED STRAIN SENSORS

SUPPORTING AT-HOME REHABILITATION EXERCISES

Master Thesis
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ABSTRACT

The process of physical rehabilitation in most cases consists of visits to a physical therapist and exercises the patient is expected to perform at home. To increase or maintain strength or flexibility these exercises need to be performed regularly. Practice teaches us that not all patients succeed here. In this project, we look into what is keeping them from succeeding and how we can support this process.

In literature, four categories of barriers are described, from which the psychological barriers are most interesting to investigate further within this project. Motivation plays a big part within this category.

The Fogg model gives structure to the different components of motivation and different factors influencing the execution of preferred behavior. It shows us triggers will fail if motivation is low or the task takes too much effort to complete.

In a lot of the cases, the intention to complete the exercises is present with the client, but the behavior does not reflect this intention. The intention-behavior gap can be bridged the same way the fogg model suggests triggers to be efficient, by motivating the user or making the task take less effort.

By providing support during the exercise - providing both motivation and decreasing effort - and giving the patient the opportunity to track their progress after doing the exercises for a longer amount of time we can increase the exercise adherence.

To provide support, we need to gather data on the movements that are made during the exercise. We developed a textile stitched strain sensor that tracks the angle of a joint. The sensor has conductive thread stitched in a tight zigzag pattern onto Kinesio tape. Since the tape is adhered to the skin, the sensor experiences minimal hysteresis.

Using the data gathered by the stitched strain sensor, we tested giving back different kinds of feedback using two different actuators. We found that giving the test subjects more precise data on their movement made them more accurate, but at the same time, made them experience their movement as less accurate. This on the one hand, gave them more motivation to improve, but also made them less confident in performing the exercise.

The project proves that using the real time data gathered by the stitched strain sensor can add to better executing of on exercise and has potential to with that data also contribute to long term exercise-adherence.

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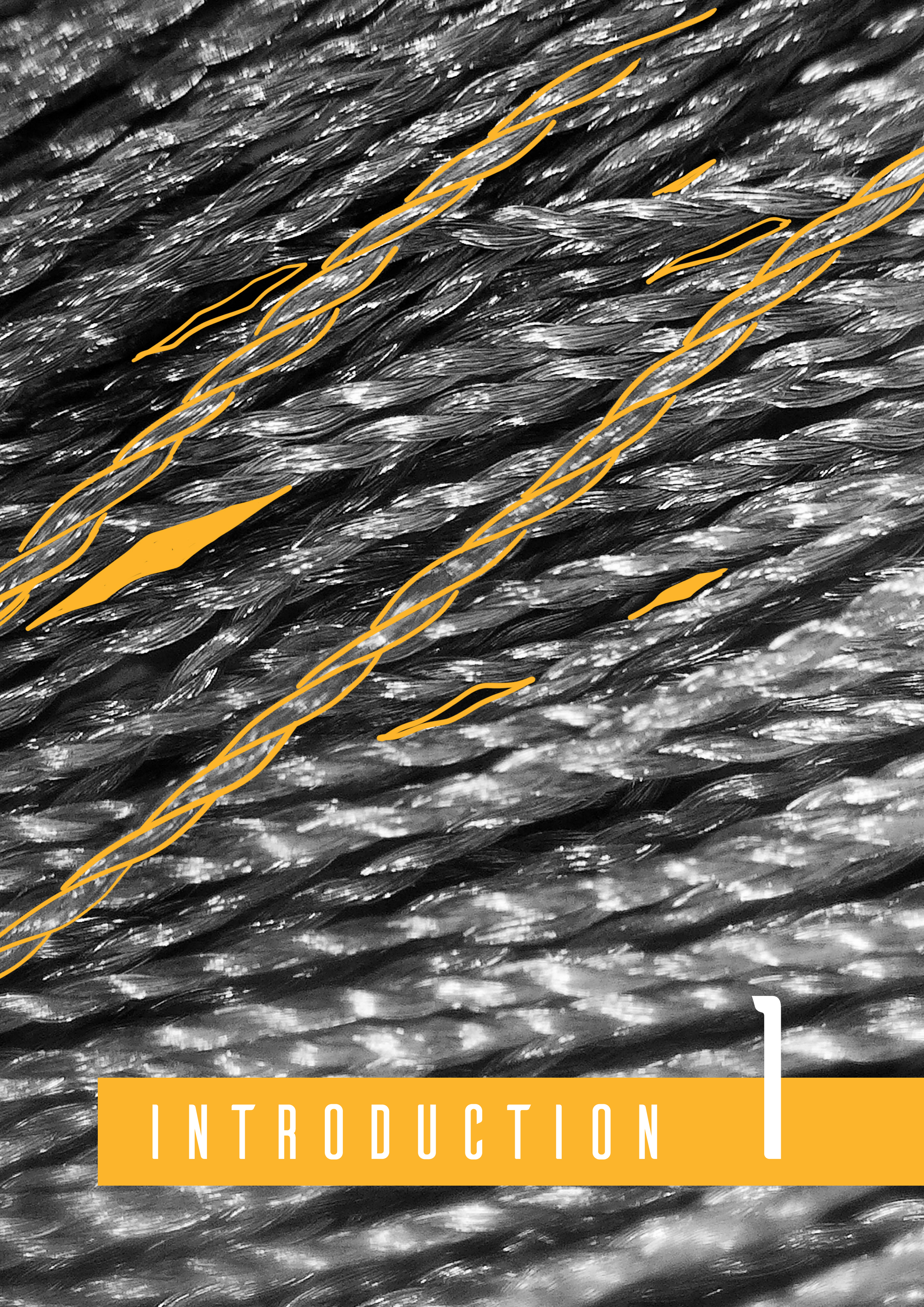


1 INTRODUCTION

1.1 AT-HOME PHYSICAL REHABILITATION

After people suffer an injury or go through surgery, physical therapy can help them to make sure they get (back) to a desired level of muscle strength or range of motion, or to reduce pain. This therapy normally consists of visits to the physical therapist office in combination with at-home-exercises.

At the physical therapist's office, the patient gets direct feedback on their movement and is motivated by the presence of the physical therapist to perform the exercises as precisely as possible. During this visit, the physical therapist adjusts the exercise to the ability of the patient and they can compose an exercise schedule together.

Yet, when the patient takes these exercises home, there is no-one telling them to start the exercises, finish them or execute them in the correct way. In practice, the adherence to these exercises is not optimal. Patients experience a diverse range of barriers (Jack et al., 2010), varying from not finding the time, to physically being unable to perform the exercise. This can cause them to not perform the necessary exercises.

In this project, the at-home experience of patients will be examined and a solution will be developed to support them with initiating and performing the exercises.

SMART TEXTILES 1.2

New advancements in the field of wearable technologies and smart textiles gives way to a broad array of possibilities (Niknejad et al., 2020). Where this technology started out as bulky sensors on tight fitting sport clothing only accessible for the high end user if accessible at all, we are currently moving toward smaller, less expensive, less obtrusive and more accessible options.

A knitted strain sensor was developed recently (Valk, 2020) which opens up the possibility to have an unobtrusive, smart wearable without the hassle or bulk of its predecessors.

Helping patients overcome some of the barriers they face, and reducing the amount of patients not adhering to their program, would have a bigger impact than just the patient benefitting from a faster recovery -and thereby needing less appointments- and the physical therapist experiencing better results from their patients.

Directly, other patients could benefit, since they will be able to get an appointment more easily.
Outside of the physical therapist's office, also the direct social- and work-environment of the patient can benefit from a faster recovery when the patient is able to join in on activities or can be self-sufficient in their daily lives.
Lastly, health insurance agencies can save funds on patients who need fewer appointments and experience a faster recovery. When people make sure their injury is fully healed, they are also less likely to get back into the healthcare system.

A visual overview of the stakeholders can be found in figure 1.1.

In addition, developing a suited stitched strain sensor to support the user during their physical rehabilitation adds to the development of smart wearables in different contexts.

GOAL 1.4

Combining the context of executing rehabilitation exercises at home and the new technologies being developed in the field of smart wearables to bring the motivation patients experience in the office of the physical therapist to their home situation.

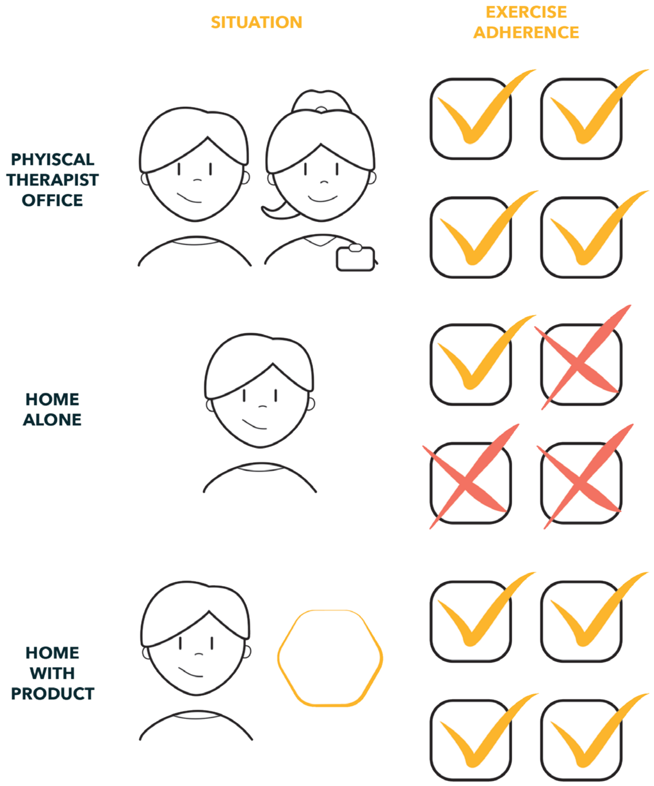


Figure 1.2 | Visualization of the goal

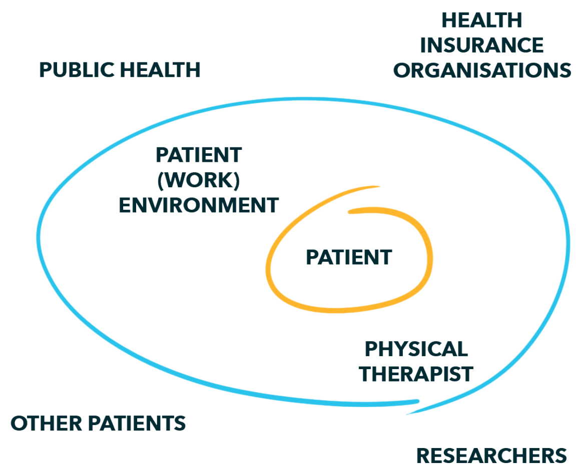


Figure 1.1 | Stakeholder Overview

1.5 APPROACH

This project will focus on combining a context with a newly to be developed sensor. For this reason both fields will first be explored, after which they can be combined to achieve a preferred situation. In this short overview, the corresponding section of the report will be indicated by the chapter and paragraph number between brackets.

Following the triple diamond method (Sanders and Stappers, 2012), the current context is explored in relevant literature (2.2) and by using interviews (2.3) with both patients and physical therapists. This combined leads to an overview of the current obstacles and ways people deal with those obstacles, finding a focus for the project and constructing a design vision (4).

With this design vision several requirements (5.1) are constructed for the textile strain sensor. This phase focuses on developing a stitched strain sensor to meet these requirements, combining different options of thread, stitches and substrates (5.3-5.5). Overcoming different hurdles to stitch the sensor and evaluating the different options to fit the context.

Gathering the data needed to provide feedback is taken care of by the developed sensor. To return this data to the user in a way it supports them during the exercises is explored in the last of the three diamonds. Exploring what feedback is useful (6) and in which way the user feels supported and motivated was done using a working prototype and testing the different scenarios (8).

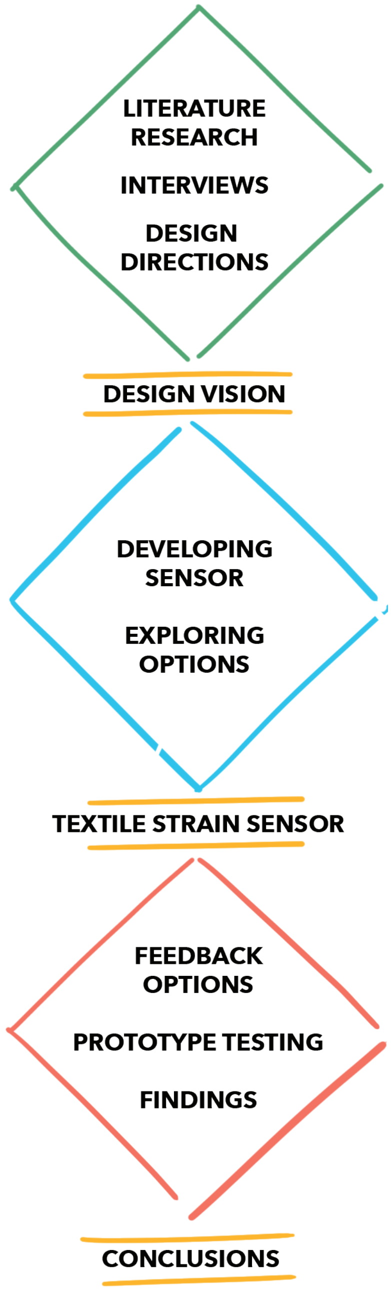
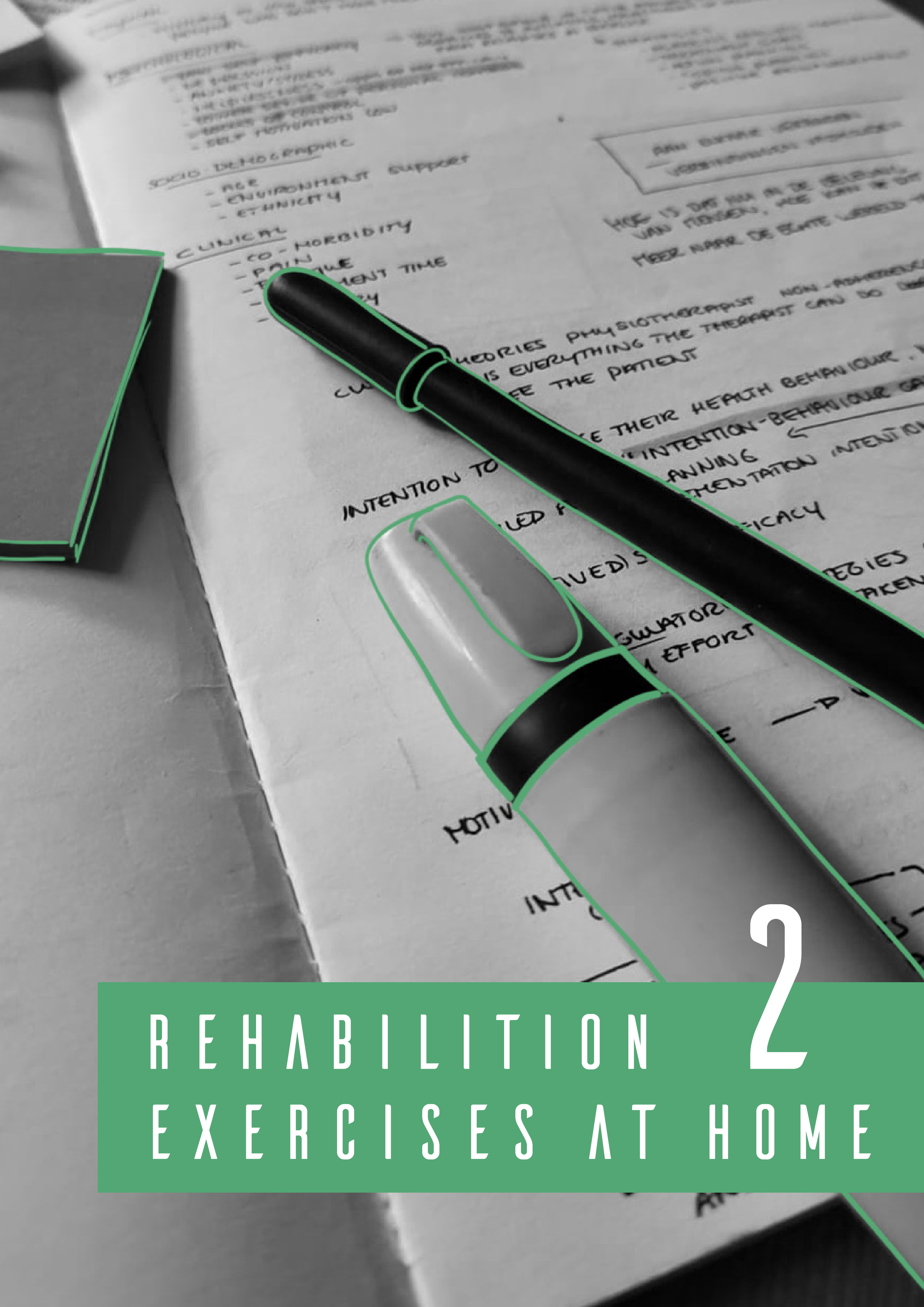


Figure 1.3 | Project Overview



2

REHABILITION EXERCISES AT HOME

To get a grip on the current situation, two different sources were consulted. Firstly, mapping literature to find what has been researched in the past relevant to the subject. To get a more personal view on the context, semi-structured interviews were conducted with several patients and two physical therapists. These insights are combined to make an overview of the current obstacles and solutions. This to determine where this project can make an impact on the experience of the user.

2.1 RESEARCH QUESTIONS

As mentioned before, we want to have a look at the causes of low exercise adherence. Since exercise adherence has a big impact on recovery of patients, research has been done on the possible causes.
The main question we want to answer is:

Why is at home exercise adherence low and how can we increase this?

This question consists of two parts, a "why" and a "how". In both the literature research and the interviews the focus will be on the first part of this question. The second part will be touched upon by exploring how the physical therapists and patients are currently solving these problems.

Why is at home exercise adherence low?

Which barriers do patients experience during at-home exercises?

How can we increase the exercise adherence?

What are solutions found in theory to increase exercise adherence? How do patients and physical therapists currently overcome these barriers?

LITERATURE RESEARCH 2.2

In the following sections, I will first discuss key barriers to exercise, including the Fogg model and the intention-behavior gap, leading to a comprehensive overview of the main qualities related to motivation.

Barriers 2.2.1

To get a grip on the different barriers people can experience during at-home rehabilitation, Jack et al. (2009) conducted a systematic review including twenty studies investigating barriers to treatment adherence.
They divided the different causes into four categories that will be individually discussed below

Physical barriers
People who had a low level of activity before the treatment started are less likely to adhere to the prescribed exercises over time. In these cases, short term (first weeks) adherence was a good indicator of long-term (one year) adherence. More competitive athletes, when compared to recreational athletes, were more likely to adhere to the exercise program.

Psychological barriers
The barriers belonging to this category can be more all-encompassing, like a high level of depression, helplessness, anxiety, stress or low self-motivation reducing the general adherence.
Some psychological barriers are more specific to the exercises themselves. If a patient has low confidence in their ability to overcome obstacles to initiate, maintain or recover from relapses for the execution of the rehabilitation program, we speak of low self-efficacy. This is something specifically related to this context, since someone can have low self-efficacy when it comes to one task, but high self-efficacy when it comes to another.
The locus of control is also important and related to this context. When someone feels they don't have any control over the situation, their locus of control is external. They expect their physical therapist to solve the problem or the discomfort they are experiencing. When their locus of control is internal, they feel like they can change the situation and are more likely to act on this feeling.

Socio-demographic barriers
Someone's age, living situation, social environment and upbringing also have a role in exercise adherence. Your environment can reduce or build different barriers. Working a demanding job where there is no room for exercise breaks is an example, but also not having the funds to visit a suitable location.

Clinical barriers
This category encompasses all medical barriers. If someone also has an illness or condition outside of the one they are being treated for in their physical therapy, they are less likely to adhere to the exercises. Also when they experience pain or fatigue during the exercises, patients are less likely to finish their program.
The treatment time also contributed to the adherence, the shorter the predicted time, the more patients are willing to perform the exercises. Also the amount of injury's someone has experienced during their life can influence their adherence. People with a first time injury are less likely to stick to their program.
If someone experiences greater discomfort in their daily lives or activities from their injury they are more likely to adhere to their exercise schedule.

In this project, we will not focus on changing the context in which the exercises take place, so physical, sociodemographic and clinical barriers are outside of the scope. This leaves the psychological barriers to further investigate. Pre-existing conditions like stress and depression also fall outside of the scope, since these conditions are not related to the specific exercises we want the clients to perform. They do have an influence on the adherence, just like all other context factors, so we will have to keep them in the back of our mind during the project.
Narrowing our field to motivation (to do the exercise), self-efficacy and the locus of control.

2.2.2 **Fogg Model**

Motivation, ability, and triggers can help us understand what drives people to show a certain (preferred) behavior according to the Fogg Behavior Model (FBM) (Fogg, 2009).

This model is visualized in Figure 2.1, showing motivation as a variable on the vertical axis and ability as a variable on the horizontal axis, both ranging from low to high. The line indicated the threshold where triggers will and won't work.

There are three core motivators that influence the motivation of an individual according to the FBM, with every motivator having two sides.

Pleasure/Pain
The result is immediate and there is little thinking or anticipating.
If an exercise immediately relieves or causes pain, this motivator is in play.

Hope/Fear
Focuses on the anticipation of an outcome, good or bad.
Anticipation of healing from an injury or fearing the injury prohibits you from doing what you enjoy.

Social Acceptance/Rejection
People are motivated to do what gives them social acceptance and avoid what leads them to social rejection even more.

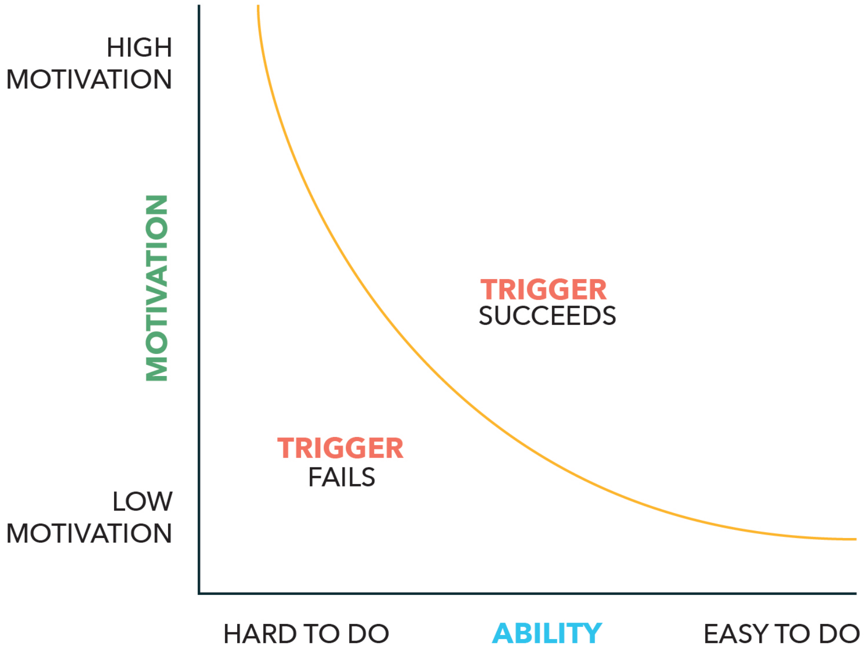


Figure 2.1 | Fogg model

The ability of an individual to perform a certain preferred behavior is influenced by Elements of Simplicity.

Time
Does the patient have time to perform their exercises.

Money
If the exercises require a fitness subscription or other materials, can the patient afford this?

Physical Effort
The exercises require physical effort regardlessly, but more difficult exercises influence the ability more than easy small exercises.

Brain Cycles
If a new exercise is complicated and requires full attention and thinking from the client, it gets more difficult.

Social Deviance
Going against the norm, maybe performing the exercises in public or taking more small breaks during work can make an exercise more difficult to perform.

Non-Routine
If something is not part of the routine of a client, it becomes more difficult. In our situation, this is almost always the case.

These elements of simplicity are different for every individual and every situation. As Fogg puts it "Simplicity is a function of a person's scarcest resource at the moment a behavior is triggered."

At this moment, as implied by the above statement, a trigger occurs. Wether or not the trigger will succeeds depends on where in the model we are.

Signal
A trigger that simply reminds someone of a behavior.
This trigger is only succesful when the situation is already on the right side of the threshold.

Spark
A trigger that increases motivation by using one (or more) of the motivators.
This trigger is useful, when the ability is high, but the motivation is low.

Facilitator
A trigger that increases ability, by using one (or more) of the elements of simplicity.
This trigger is useful, when the motviation is high, but the ability is low.

2.2.3 Intention Behavior Gap

Often when people start out at the physical therapist they have every intention of following the prescribed program they receive. In practice, this proves to be more difficult to realize than initially estimated. This discrepancy is called the Intention-Behavior Gap.

Sniehotta, Scholz and Schwarzer (2005) suggest different methods to bridge this gap in the context of physical exercise. The solutions they describe are mainly focussed on planning and self-efficacy. These interventions mainly take place in the office of the physical therapist and should lead to patients self regulating at home using the tools they were handed.

In this research, we want to further look into supporting the user in their own home and if the content of the exercises or the way they are presented can influence the behavior and bridge the gap.

Conclusions 2.2.4

We started this literature research with the following question:

Which barriers do patients experience during at-home exercises?

In literature, four categories of barriers are described, from which the psychological barriers are most interesting to investigate further within this project. Motivation plays a big part within this category. The Fogg model gives structure to the different components of motivation and different factors influencing the execution of preferred behavior.

To gather experiences and examples of how patients currently follow their rehabilitation programs, semi-structured interviews were conducted in the next section.

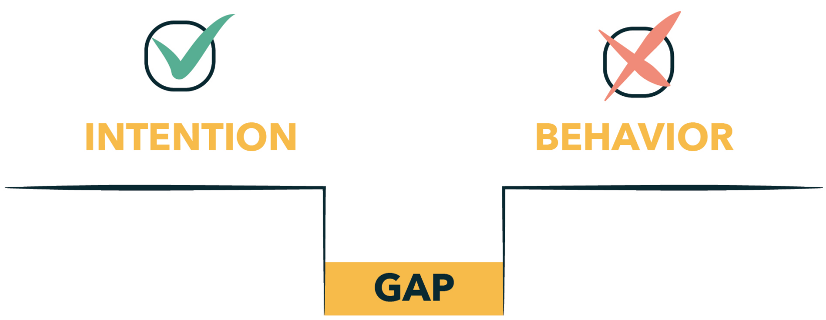


Figure 2.2 | Intention Behavior Gap

2.3 INTERVIEWS

To bring the theoretical knowledge gained into a practical context, interviews were conducted with physical therapists and people who had to go through -or are going through- physical rehabilitation.

Revisiting our research goal, in this part we want to focus on mapping the current situation and looking for the solutions that are currently put into practice.

Why is at home exercise adherence low and how can we increase this?

What barriers do patients experience during at-home exercises?
Which solutions do patients find to increase their adherence?

2.3.1 Approach and method

Because experiences concerning the different rehabilitation programs the interviewees have followed can look very different, a semi-structured interview was conducted. This way there is more room to explore the experiences and themes connected to this topic.

The following themes were discussed during the interviews:
(For the full Framework of the interview, please visit the Appendix.)

Situation - Making an overview of the general context. When, why and how were you treated by a physical therapist.
Intention - What was the initial mindset of the interviewee concerning tasks they needed to execute at home?
Planning - How did they plan to do the exercises, did they have any help during the rehabilitation at home?
Execution - Did they execute the exercises as intended?
Reflection - Did they fulfill their own expectations and would they change anything?
Possibilities - What would be an ideal situation in which they were confident they would execute all the exercises as intended?

The interviews were conducted with six participants. Two are physical therapists working in different offices and four are patients who are -or were- following a rehabilitation program at a physical therapist with exercises that needed to be performed. All were female and adults. The patients all participate in a teamsport.

Due to pandemic related restrictions, all interviews were conducted by means of (video) call. These were recorded with consent of the interviewee. One of the recordings was regrettably not usuable to be transcribed.

After conducting the interviews, a transcript was made from 5 out of 6 interviews so quotes could be selected and by using statement cards (Sanders et al. ,2012), interpreted and sorted into categories to turn the raw data of the interview into information to use during the project.

The statement cards were clustered using the categories previously discussed in the Fogg model. All quotes used in this report are translated from Dutch to English.

2.3.2 Statement Cards

As mentioned, the quotes were placed onto statement cards and sorted using the elements present in the Fogg model. In the next segment, we will visit every element and give an interview quote that matches this theme. Also a short explanation was added to place the different elements into our context. All statement Cards sorted by theme can be found in the Appendix.

Motivation

Social Acceptance
"She pushes me when I don't feel like it and makes me go. If she doesn't feel like it, I will push her to go with me."
The presence of the PT during the performance of exercises or someone that also has to perform a similar task, will make motivation higher.

Social Rejection
Having to admit to the PT that the exercises weren't performed that were discussed the last session, causes a negative feeling that people want to avoid.

Anticipation - Hope
"The motivation to quickly, as quickly as possible, solve my injury, for me was a really important motivator."
The hope to get rid of an injury, trust in the effectiveness of the exercises that need to be performed, and trust in the PT are important motivators according to the interviews.

Anticipation - Fear
The prospect of not being able to for instance walk, or execute daily activities, increases motivation.

Sensation - Pleasure
"I will for example straighten my leg, with a counter weight, and then I'll ski (on screen). Really fun. I'm not really good at it, but it makes it a lot more fun."
Different examples of gamification and tracking methods that are used during the PT visit to motivate clients to perform the exercise to the best of their ability. No examples of similar methods to use at home were given.

Sensation - Pain
"This is one of my injuries that just causes a lot of irritation, so I have to say I'm always very motivated to make sure that it is not present."
Pain can motivate clients when they experience pain and the exercise makes sure it decreases. On the other hand, experiencing more pain specifically during the exercises can make someone not want to start or complete their exercises.

Ability

Social Deviance
Doing the exercises in the middle of the work floor, may be frowned upon by colleagues or clients. This leads to less opportunities to fit in the different exercises.

Physically Demanding
All physical therapists in the experience of the participants adjust the exercises to the client to make sure they are able to perform them. Getting home after a long tiring day of work does however influence the ability to start the exercises.

Time
"But you notice concerning the time I'm thinking; When am I supposed to do this?"
Having the time to execute the exercises attributes to the adherence. Also, knowing how long an exercise is can also help to increase the ability, since it makes planning easier.

Money
Using the expensive equipment at the PT's office or the gym can make exercises easier to perform, but all PT's keep in mind the facilities someone has to their disposal when compiling the exercise programs.

Cognitively Demanding
When tasks are easy to comprehend and remember, the clients would more frequently perform them. When they got harder and some maybe needed to look up what they needed to do, the exercise adherence decreases.
Also having to remember the correct way of executing the exercise and checking yourself if during the performance of the exercise can give extra cognitive pressure.

Non-Routine
When a client has a set daily rhythm it is easier to plan the new exercises within that schedule. Others linked the exercises to an existing habit or space, which made it more difficult to follow.

Triggers

Sparks
Making the exercise more fun or reminding the person of the hope they have for the outcome of their activities.

Facilitators
"The thing is, you don't know if you do the exercise correctly. That was something I thought was a pity"
Solutions like putting the equipment you need in the space you will use to exercise can facilitate the activity. Also giving feedback so clients have to think less about the workout they are doing increases the ability.

Signals
"Switching off an alarm is very easy and it doesn't bother me after that if I did or didn't do the exercises."
Alarms and notifications were mostly found to be annoying or badly timed, causing frustration and are easily shut off. None of the interviewees indicated signal triggers to work.

Conclusions 2.3.3

Almost all categories of the Fogg model are represented in the data found during the interviews. The biggest motivators in play in this context are hope and pain. Hope to rehabilitate as fast as possible and pain that constantly reminds the clients to perform the exercises.

The biggest difference between the PT's office and at home is the social aspect of having someone next to you, but also how cognitively demanding something is. At the PT's office the client is told what to do and corrected by the PT if an exercise is not performed correctly. At home exercises have to be remembered and the client has to check for themselves if the exercises are performed correctly and the prescribed amount of times.

2.4 CURRENT SITUATION

Often, people are willing to change their health behavior when they are at the physical therapist office, but when they get home and are expected to take action, this doesn't happen.

They have an intent to change, but due to risk perception, outcome expectations or low perceived self-efficacy, this intent doesn't translate to action.

This is called the intention-behavior gap (Sheeran & Webb, 2016). This gap we want to close to get to the desired behavior. For visualization purposes we illustrated this gap with a literal divide someone has to cross to get from the "intention" to the "behavior" side.

To get to the other side we have several options.

Starting with what happens when the patient is present in the office of the physical therapist (PT), learns which exercises need to be performed, and executes them for the first time.

Here, together with the PT, you build a part of the bridge you need to get to your desired behavior. This consists of the knowledge of what you need to do, why these exercises will help you recover, how you need to perform them, and the confirmation you are physically able to do these exercises.

As long as you're under the supervision of your PT, they will bridge the last part of the gap by just being there, telling you what to do and correcting you if something goes wrong.

Figure 2.3 | The Intention Behavior Gap with the patient trying to get to the other side.

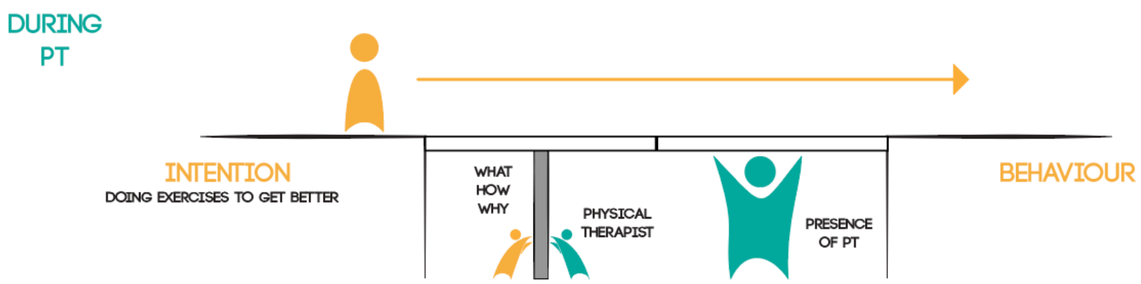


Figure 2.4 | The Intention Behavior Gap with the bridge build at the PT's office.

The moment you arrive home you don't have the presence of your PT to help you bridge the last part of the gap.

Usually, initial motivation and adherence is high. This is because all the exercises are new and you are ready to spend time doing the exercises. To illustrate this initial energy you get from the novelty of the exercises and activity, a trampoline is added to our visualization to help the patient jump over the gap.

The problem is, nothing stays a novelty forever. Over time the excitement wears off and the "bounce" reduces in our novelty trampoline, causing the patient to not always make it all the way to the other side of the gap. Over time, it starts bouncing less and less and the patient makes it to the other side less and less.

This is of course a very simplified illustration of how motivation turns intention into behavior.

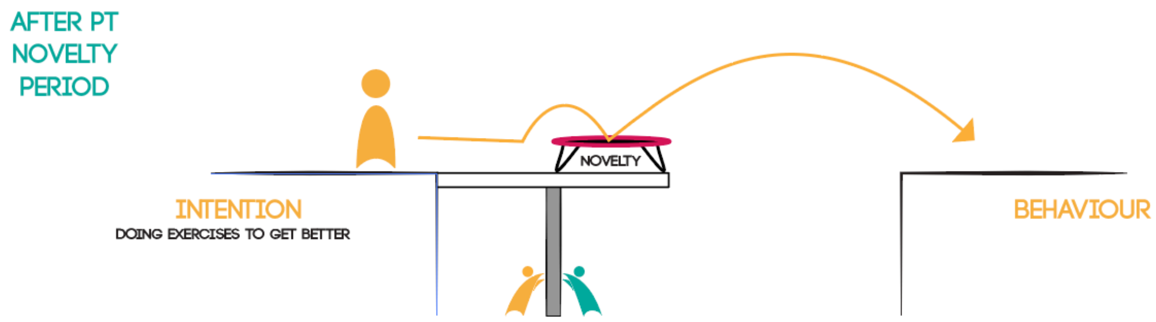


Figure 2.5 | The Intention Behavior Gap with the novelty trampoline getting you across.

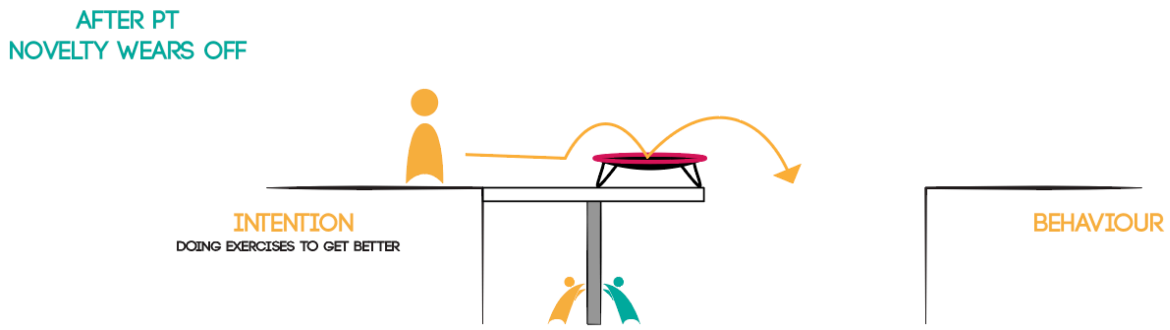


Figure 2.6 | The Intention Behavior Gap with the novelty trampoline that has lost it's bounce.

To get a more detailed image of the different motivations playing a part in this situation, we have made a simple chart. On the horizontal axes we have the time and on the vertical axes the "energy to act". This energy can be positive for different sources of motivation but can also be negative if a factor makes the exercises more difficult or less exciting.

All the values we will see in this graph will be different and relate to each other in a different way per person. One person might get a lot of energy from seeing progress happen, while another will be more motivated by the involvement of a second party that they have to keep updated, this can be the PT, a friend, or partner.

We added a horizontal line in the graph to indicate the amount of "energy" all the different factors have to add up to to cross a certain threshold. Crossing this "doing"threshold means there was enough energy to make the jump to the other side of the intention-behavior-gap.

In this overview we can now add the energy we get just from the newness of the exercises (the newness trampoline). You see the energy starts high, but as we get used to the new situation, the energy slowly gets lower until it no longer is enough to cross the threshold.

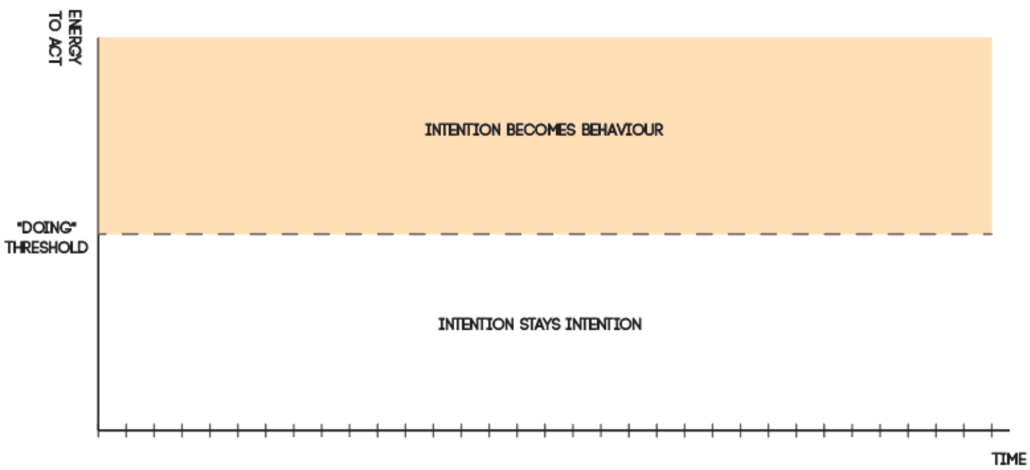


Figure 2.7 | Visualization of the "Doing Threshold"

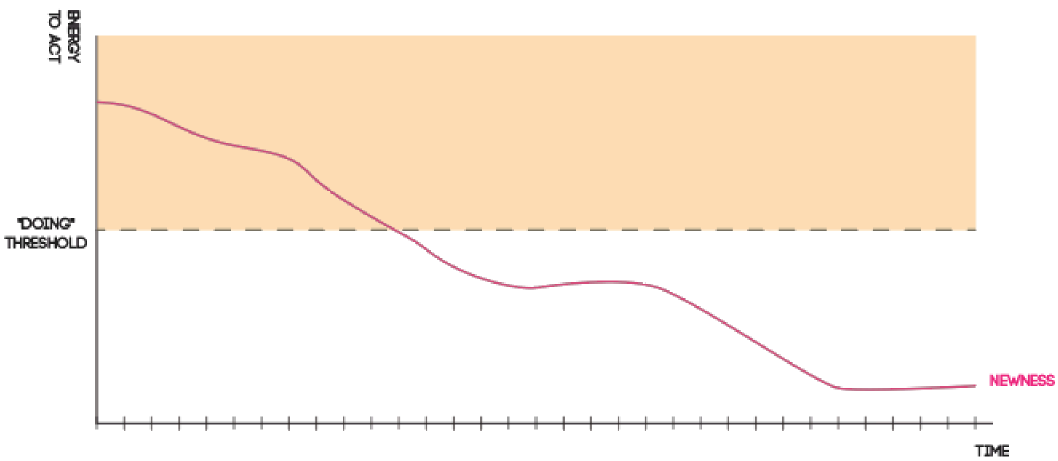


Figure 2.8 | Visualization of the "Doing Threshold" with the newness energy plotted.

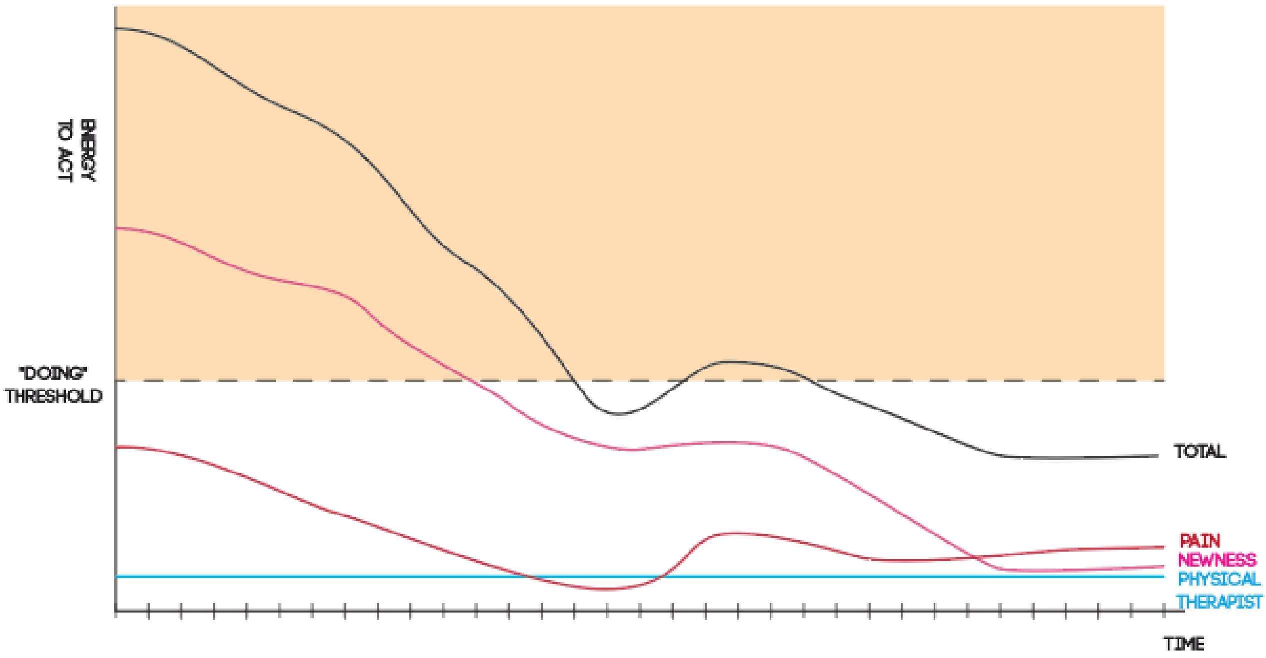


Figure 2.9 | Visualization of the "Doing Threshold" with the energy caused by newness, the PT and pain.

As mentioned before, there are a lot more factors contributing to this energy. In the next overview, we added pain and involvement of the PT.

Even when the PT is not present during the exercises, having someone in the back of your head that you feel a responsibility towards.
Some sources of motivation also get influenced by your actions. We take "pain" as an example here. Starting, the patient is experiencing pain during their day, which motivates them. By performing the exercises regularly, they reduce this pain and after a while, combined with other factors, the "doing"threshold is no longer fulfilled. When the exercises are no longer performed, this could cause the pain to return and the motivational energy coming from this source becoming higher once more.

2.5 CURRENT SOLUTIONS

Current research in this field has mainly been done on what the physical therapist can do (together with the patient) to increase exercise adherence. Examples are setting realistic expectations, setting treatment goals, action planning, coping planning and positive reinforcement.

These theories have proven to have a positive impact, but as mentioned before focus mainly on what the PT can do while the patient is at their office.

We want to research how a product can make a positive impact on the adherence outside of the office, in the environment where the exercises need to happen.

PREFERRED SITUATION 2.6

In our current situation we have the intention behavior gap that we need to overcome. Having the bridge we build with help of the physical therapist we get halfway past the gap, but it is not sufficient. We aim to build a bridge for the remainder of the gap with help of the product.

To make sure the bridge we build is sturdy enough and holds up over time, we can look back at the graphs we made earlier showing the "doing"-threshold.

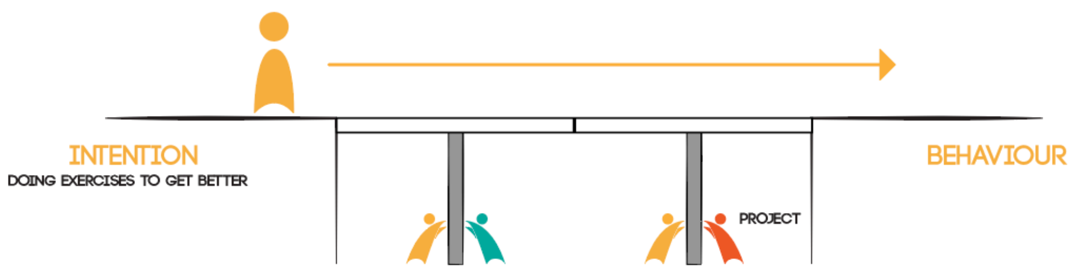


Figure 2.10 | The Intention Behavior Gap with the effect of the project visualized.

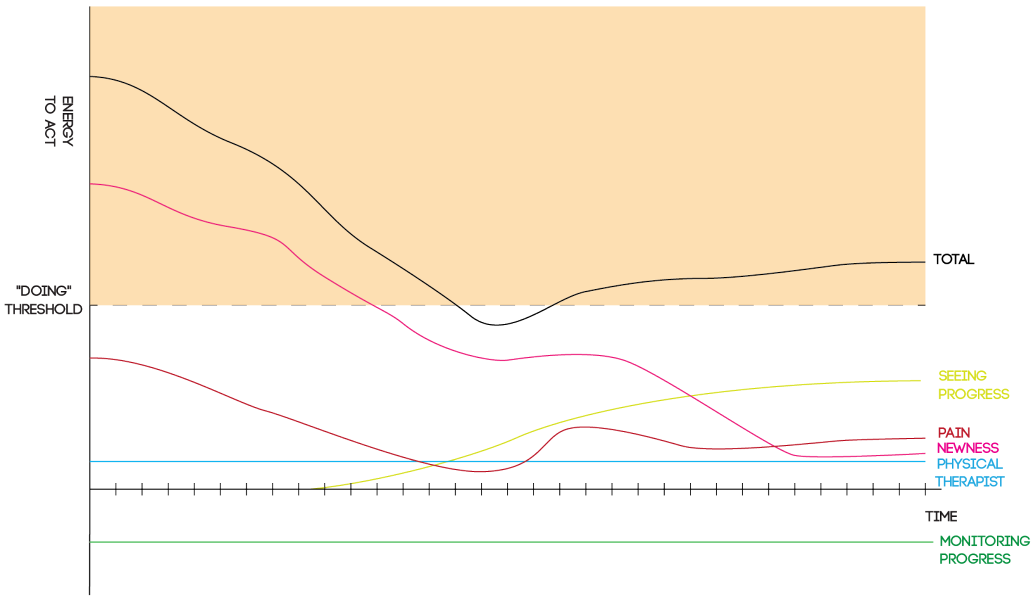


Figure 2.11 | Situation 1 - Monitoring.

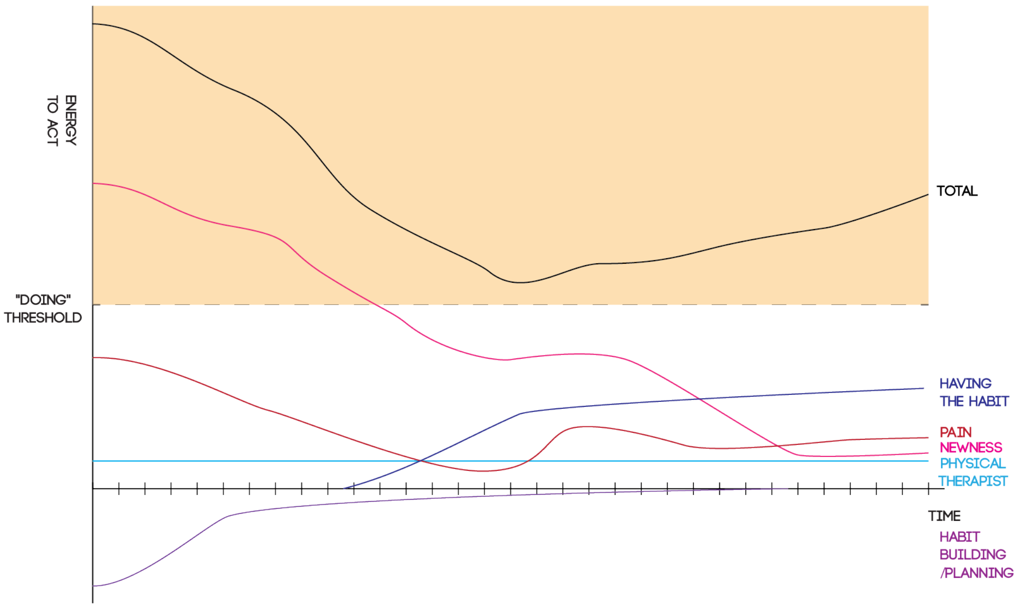


Figure 2.12 | Situation 2 - Habit building.

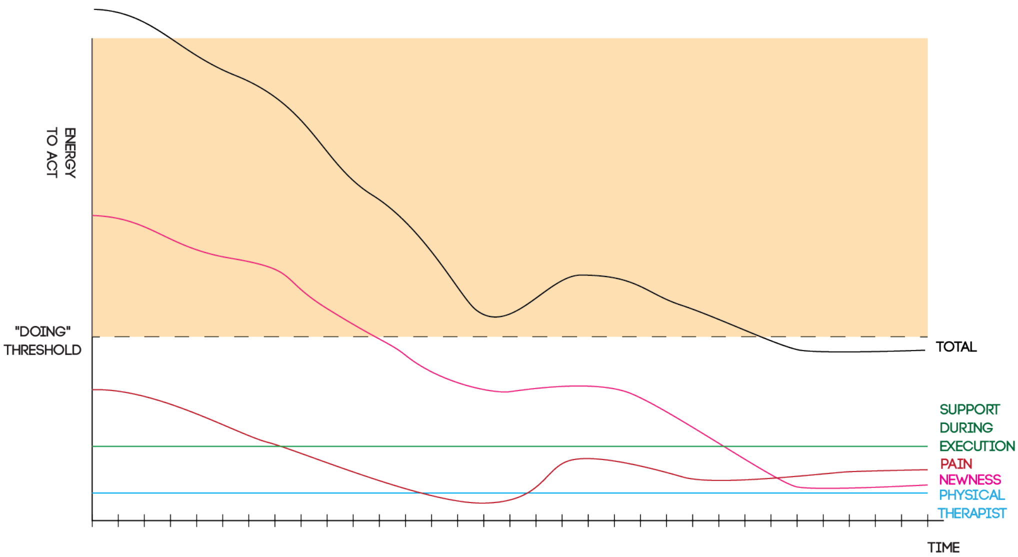


Figure 2.13 | Situation 3 - Support during exercise.

In the graphs on the left, three changes are implemented into the current situation. Situation one shows us how monitoring progress could influence the motivation. Putting in more effort to monitor will lower the motivation curve, but in the early stages, where the newness value is still high, this does not prevent the user from executing the preferred behavior.

After a certain amount of time, when the newness value is starting to decrease, the user can look back at the monitored progress and get renewed motivation from the fact they are improving.
The second situation illustrated the building of a habit. When a habit is fully formed, the ability to do the task is very high and the user will only need a small signal to start their exercises. Building a habit is difficult and requires a larger amount of energy in the beginning of the process.

The last image shows the last situation, where the product supports the user during the exercise, increasing the ability of the user to perform the exercises.

CONCLUSIONS 2.7

We looked at different sources in literature to define our scope. Motivation and self-efficacy, two examples of psychological barriers, were further explored. The Fogg model for behavior change focusses on motivation and proposes a division into motivation and ability.

This model was used to cluster the insights derived from the interviews with patients and PT's. The main difference in motivation between the PT's office and at home is the presence of the PT itself. Looking at the Ability in the situations of the interviewees, the most prominent subcategories in play were time, non-routine and cognitive demand.

After combining our findings from literature and interviews, we have an overview of what influences the users to bridge the gap between intention and behavior.

We end with three scenarios, where progress tracking (hope), habit building (non-routine), and support during exercises (cognitive demand) are represented.

SMART TEXTILES 3

All three options mentioned before depend on some sort of data input. For option one this is progress (accuracy and how many repetitions), option two tracks when the exercises are performed and option three focuses on how accurate the execution is.

If the patient has to input this data manually, it takes a lot more energy out of the equation, which could lead to patients not performing the exercises long enough for progress to show or a habit to have formed. Using smart materials to gather this input we can decrease the amount of energy it will take from the patient and make sure they do get enough exercise to see the progress and build that habit.

Smart materials can provide an unobtrusive way to gather this data, since we can integrate the sensors into clothing or a small piece of exercising equipment. There is already the possibility to for example setup a camera to track your movement, but this would also again take more energy from the user than we would like.

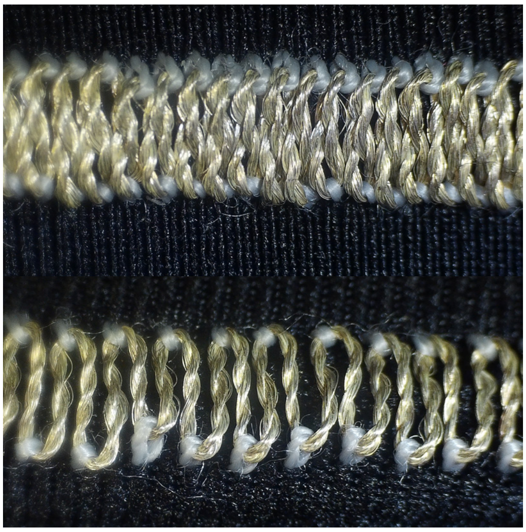


Figure 3.1 | top - unstretch sensor
| bottom - stretched snesor

STITCHED STRAIN SENSORS 3.1

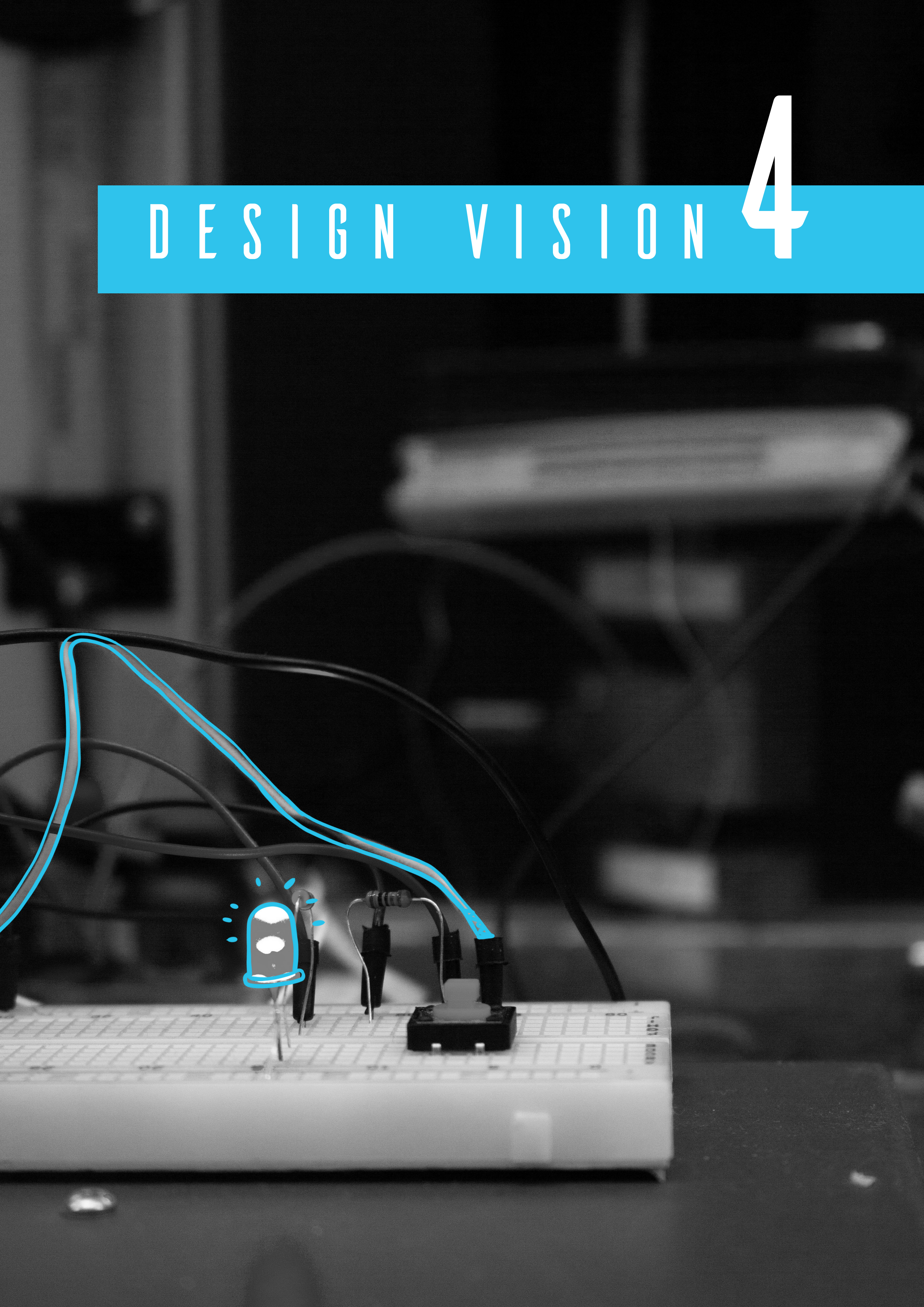
Jansen (2020) gave an overview of the current available research in knitted and stitched textile sensors. Using these insights, we had a closer look at the working of stitched strain sensors. These sensors are made using a silver coated thread, making it conductive. The threads in the strain sensor are sewn in a tight zigzag stitch, meaning the thread has a lot of surface connecting and the electric charge can jump easily from one stitch to the next, shortening the distance it travels and therefore experiencing a lower resistance. When we stretch the substrate the zigzag stitch will separate, eliminating the possibility for the electric charge to jump and take a shortcut. It has to travel further, causing the resistance to increase.
By measuring the changing resistance of this circuit, the amount of stretch in the sensor can be determined. Knowing the amount of stretch on a sensor connected to the skin of a moving joint, the angle of this joint can also be derived.

CONCLUSION 3.2

The stitched strain sensor has the ability to detect stretch in the material. To see if this material has a place in the context we added another sub-research question to our project.

Q.1.2.3. How can a textile strain sensor increase the exercise adherence?

DESIGN VISION 4



With the insights and learnings from the previous research a design vision was created to set a goal for the project.

Supporting the user during the exercises by providing **feedback on the movement**. This gives the user **confidence** in their ability to perform the task and contributes to a **better execution and faster recovery**.

Using **a textile stitched sensor** in a **minimal design** to put the focus on the execution of the exercise.

It will **initiate interaction** by **nudging** the user at the appropriate time. By **analyzing the behavior** of the user during the initial phase of recovery, where motivation is high, to determine patterns.
It provides a reminder when it's **most likely the user will execute** the intended exercises. This will result in a higher frequency of practice.

Support
The device will provide guidance and support to the user.

Feedback on the movement
The product will give real time feedback on the movement of the user, this can be visual, auditory or tactile.

Confidence
Giving the user insight into how they are performing the exercises, gives them conformation on their execution of the movement.

Better execution and faster recovery
More accurate execution of the exercise as intended will contribute to building or stabilizing the right parts of the body for a faster recovery.

Stitched strain sensor
Using conductive thread stitched onto a textile substrate.

Minimal design
Not distracting from the task and not complicating the exercises. Exercises from a physical therapist are usually very simple and only require a single movement. They also have to be executed frequently. This means the design has to make sure to not make this task more complicated by adding extra steps.

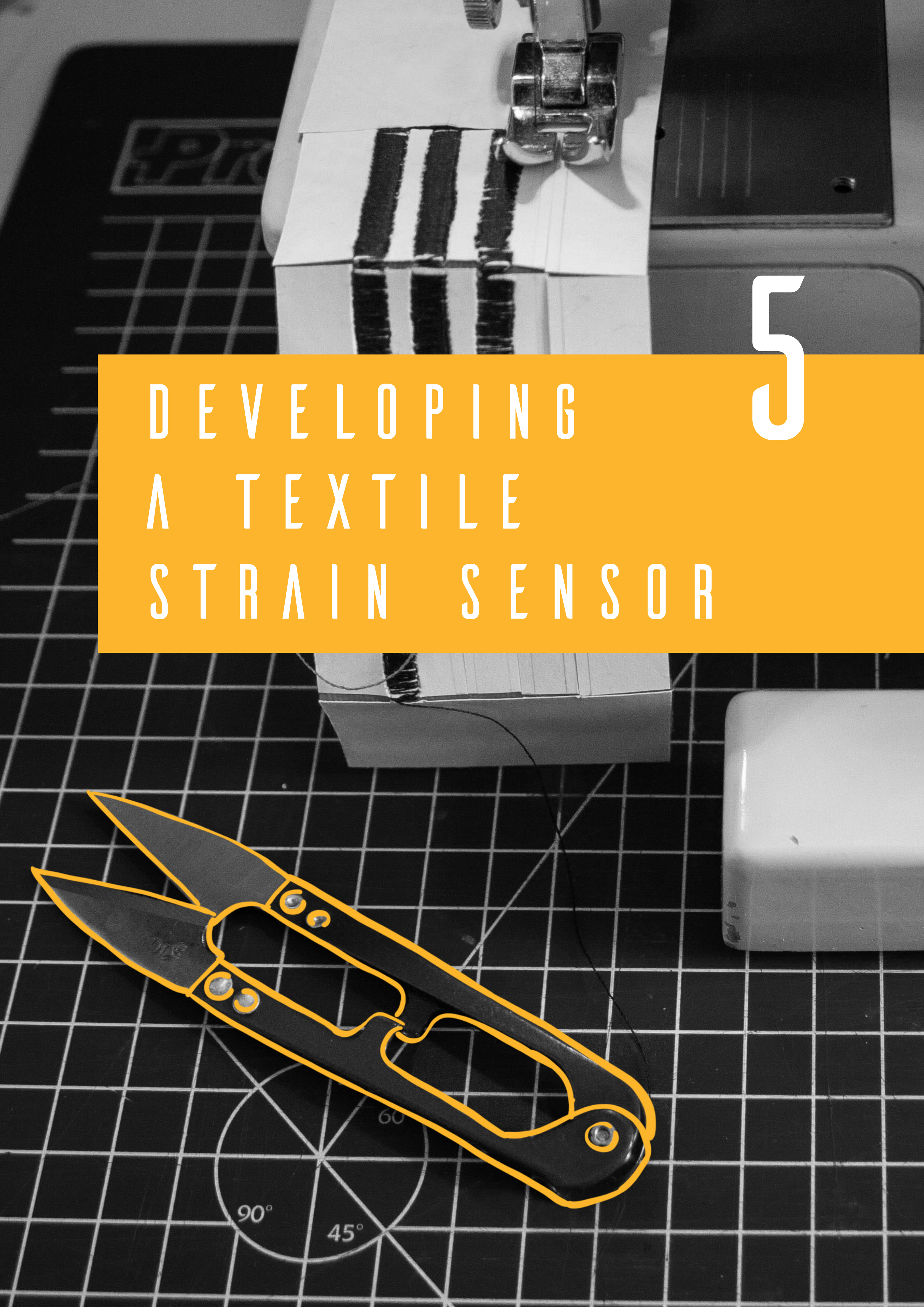
Initiate interaction by nudging
Giving the user a signal when to execute the assignment without the user having to consciously activate the device.

Analyzing behavior
Tracking when or where the exercises will most likely be performed to make sure the device reminds the user of the exercise at the most opportune time.

Most likely moment to perform the exercise
Smart products that can sense when the user has already performed their exercises, so no encouragement is needed. It could also sense at what moment it is not appropriate or useful to nudge the user. The same applies to sensing when the user didn't take action already and the moment or location lends itself well to performing the exercises. Since this will differ for every individual, a predefined behavior cannot be set, but will have to be adjusted when used.

5

DEVELOPING A TEXTILE STRAIN SENSOR



This chapter will focus on the practical development of the stitched strain sensor for this project. First we will define the requirements for the strain sensor to work properly in our scope, so a prototype can be realized further on. To test the strain sensor on these requirements

5.1 REQUIREMENTS

Previously we determined the sensor has to measure different angles of various joints in the human body to collect the relevant data needed to give feedback on the movement and progression.
To narrow down the scope for the sensor and this project, the focus is put on the elbow joint. This joint has a wide reach in degrees, moves only on one axis and is easily accessible for testing.
A rough measurement of the skin when the arm is stretched compared to the skin when the arm is bent teaches us a range of 40% is appropriate (the sample started at 10 cm and stretched to 14 cm).
In this range we want a noticeable difference in the measured electrical resistance in the sensor and the resistance to be in the range of 100 to 200 ohm, since we are working with a system t
The Arduino we are using in the prototype can measure on a scale of 0 to 1024, with 0 being 0 volts and 1023 being 5 volts. We are using a simplified circuit with a known resistance and the sensor.
Over time we want the strain sensor to stay stable in its given value.

TESTING 5.2

To make sure the sensor will work and give a fitting range of data points, two test setups were used. To test if the resistance of the sensor is in the right range and if it changes significantly enough when stretched, a simple setup was used consisting of a multimeter and a stretch plane. Both ends of the fabric were secured between clips, with the multimeter attached to the conductive thread directly. One clip was held in place, while the other moved straight up and down, stretching the fabric in one direction. This gave a first indication of the suitability of the sensor.
When a set of sensors was determined that looked promising using the multimeter, we moved to the LETT (Low-End Tensile Tester). This gave us the opportunity to stretch the fabric to a precise distance and gather the resistance data.

CONDUCTIVE THREADS 5.3

Previous research (Gioberto 2016/ Dupler 2019) into conductive thread and its application for a textile strain sensor has yielded a preference for nylon thread covered in a layer of silver. Shortly different threads were tested, but conform the findings in literature 2 ply Nylon-Silver Shieldex was found to deliver the most reliable measurements.

Figure 5.1 | Types of conductive thread

5.4 STITCH TYPES

In the lab a Brother Innov-is 100 is present. The different (stretch)stitch types on this machine were tested for applicability. The simple zigzag was the most promising, as the others couldn't get the thread close enough to each other to allow the current to make the shortcut or were bunched up too much which caused only a minimal shift in resistance.
The stitch width was set to the maximum of this machine, 6 mm.
The machine broke down unfortunately during the conduction of this research. A personal machine was used. This machine has a similar stitch width, but was not digital, so the values were estimated.
The top thread of the machine was set to a standard nylon thread with a thickness approaching the thickness of the Shieldex to minimize differences in resistance in the machine. The bottom thread was set with Shieldex. The nature of the silver coating on the Shieldex gives it more resistance in the machine and the more the thread rubs against different components and moving parts of the machine, the more of the silver coating comes off the thread. Setting the Shieldex thread as the bottom thread would ensure it to have less contact points with the machine during sewing, so less resistance and more coating remaining on the thread.

SUBSTRATES 5.5

"Jersey knitted substrates containing 10-25% elastomeric (Spandex) yarn" was the best performing substrate found in previous research. (Jansen, 2020).

In the first tests an array of different stretch materials were considered. In the table below an overview of different fabrics and machine settings are found with the relevant resistor value.

Using the lycra substrate brought some complications to the construction. The tension needed on the thread to get a clean stitched sensor would cause the substrate to give in, shrink and make the stitches irregular. To stiffen up the lycra when stitching different methods were considered. A backing produced for embroidery was considered, but in embroidery this remains between the stitching, which was undesirable for our situation, since we want to retain the stretch of the substrate. A water-soluble-fusible-interfacing (soluvlies) was used to back the lycra and was dissolved in water after the sensor was stitched on the substrate. While rinsing the sensor, attention was paid to stretching the sensor as little as possible to retain the shape. The sensor was rinsed under running water. When placed in a container of water, the glue and residue of the interfacing would adhere to the whole sample and would influence the stretch of the substrate.

After conducting different tests with lycra and stitch types a sample was accomplished with a proficient resistance range and stretch.
For the attachment to the elbow joint a tight fitting lycra sleeve was considered, as well as a solution with removable velcro straps.

This sleeve would stay in place for a short amount of time, but would curl up. Some silicone strips would probably aid in resolving this problem.
Another bigger issue with this adherence solution is the calibration. Since the user will be taking this band off and putting it on again the next day, the placing will be slightly off and calibration of the device would require more energy from the user and remove us further from crossing the "doing-threshold".

A solution to this issue would be attaching the sensor to the joint with a custom fit brace that could only be worn one way, or attaching it to the skin in a more permanent way. The last option was explored by using Kinesiotape as a substrate. This is a cotton one-way-stretch sporttape, made to replicate the skin (130-140% stretch), can be worn for a couple of days by the patient without being removed and is applied by a physical therapist a lot of the time.

Figure 5.1 | armband made of lycra

Figure 5.2 | armband with two seperate straps

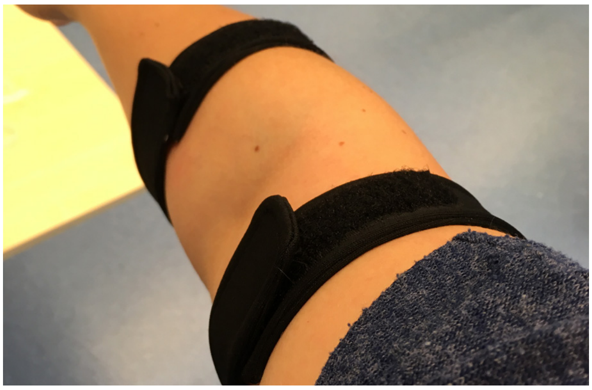


Figure 5.3 | two seperate straps (underside)

Figure 5.4 | first prototype using tape

This substrate stitched with little problems, since the backing of the tape was sturdy paper, which made sure the substrate would not stretch under the thread tension of the sewing machine. The water-soluble-backing was not necessary, but the paper backing of the tape was a lot harder to remove. Using the water-soluble-backing was also not an option because the water would affect the adhesive property of the tape. By pre-cutting the paper backing of the tape before stitching, controlled stretching of the tape after stitching and patience using a sharp pointed tweezer, the paper backing could be removed while keeping the sensor intact.

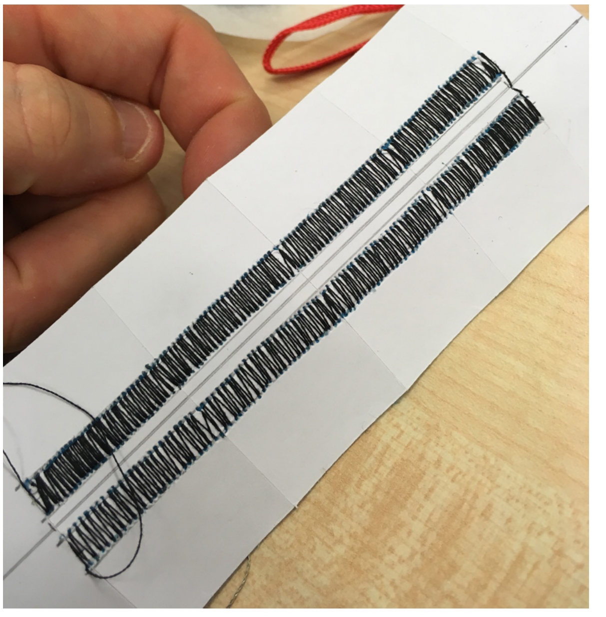
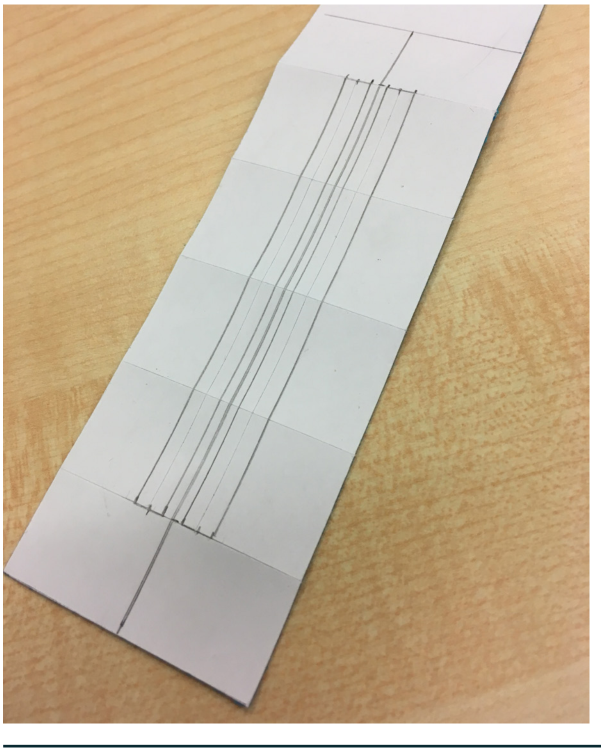
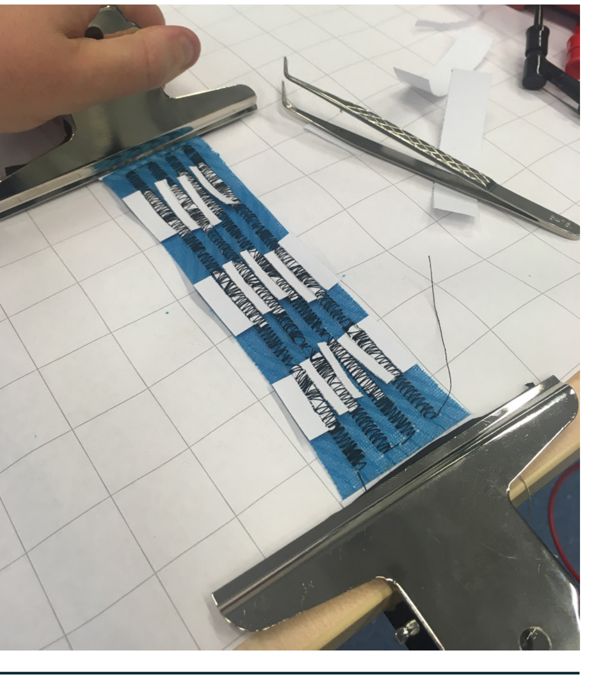


Figure 5.5 | left | kinesiotape prepared for sewing
Figure 5.6 | top right | stitched tape
Figure 5.7 | middle right | stitched tape
Figure 5,8 | bottom right | removing backing





5.6 TEST RESULTS

The first promising measurements came from a single line of zigzag stitching on lycra. The stitchwidth and stitchdistance were determined here. The stitchwidth is 6 mm, which is the widest stitch the machine will allow for, and the stitchdistance 0.6 mm. The length of the stitchline here was 9 cm.
In Figure 5.9 shows the Resistance measured for this sensor.

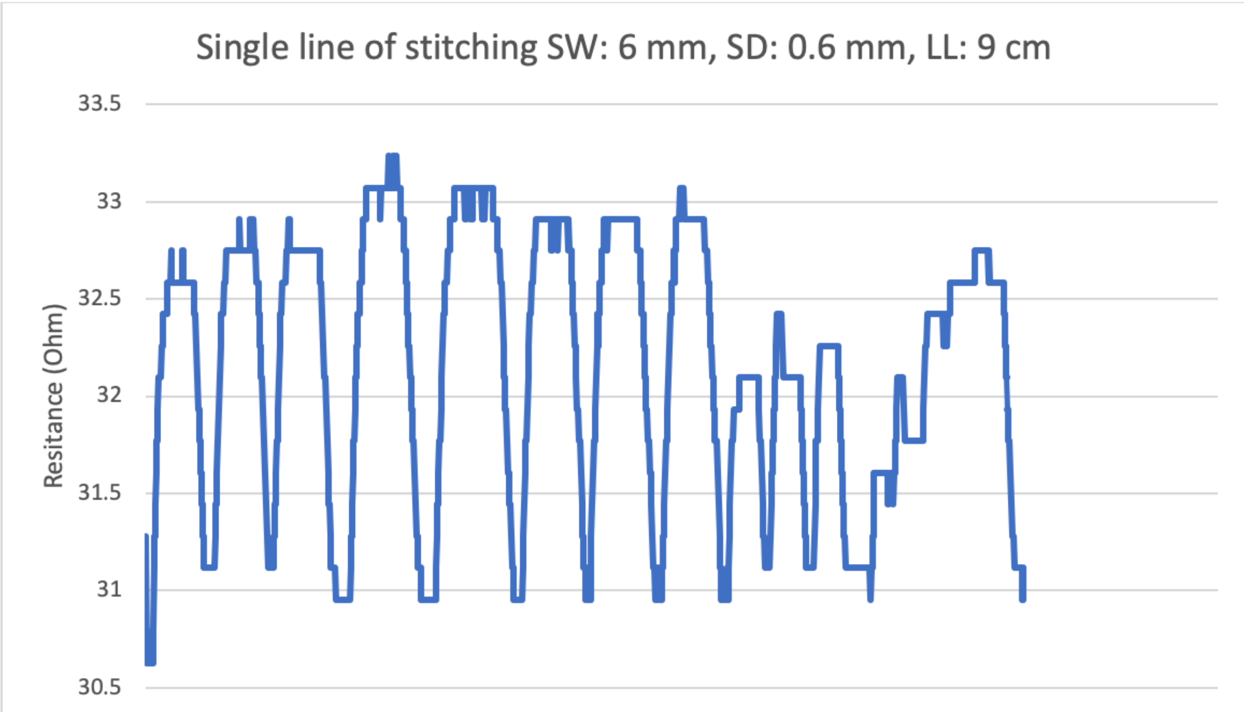


Figure 5.9 | Single line of stitching on Lycra LETT measurements

After switching substrates, more measurements were done on the sensor. Figure 5.10 shows us the resistance measured with the sensor stitched on kinesiotape.

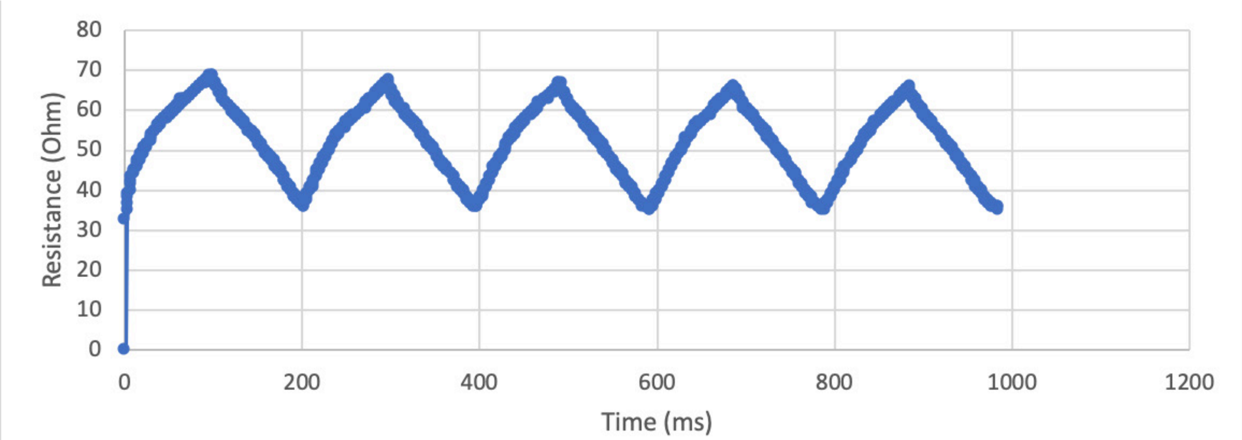


Figure 5.10 | Single line of stitching on KInesiotape LETT measurements

An important way to determine the quality of the textile strain sensor is the Gauge Factor.

$$Gauge\ Factor = \frac{\Delta R/R_0}{\varepsilon}$$

We used one of the repetitions of the previous sensor and plotted the ΔR/R0 over the Strain in percentages. This shows us the working range of the sensor is between 0% and 35%.

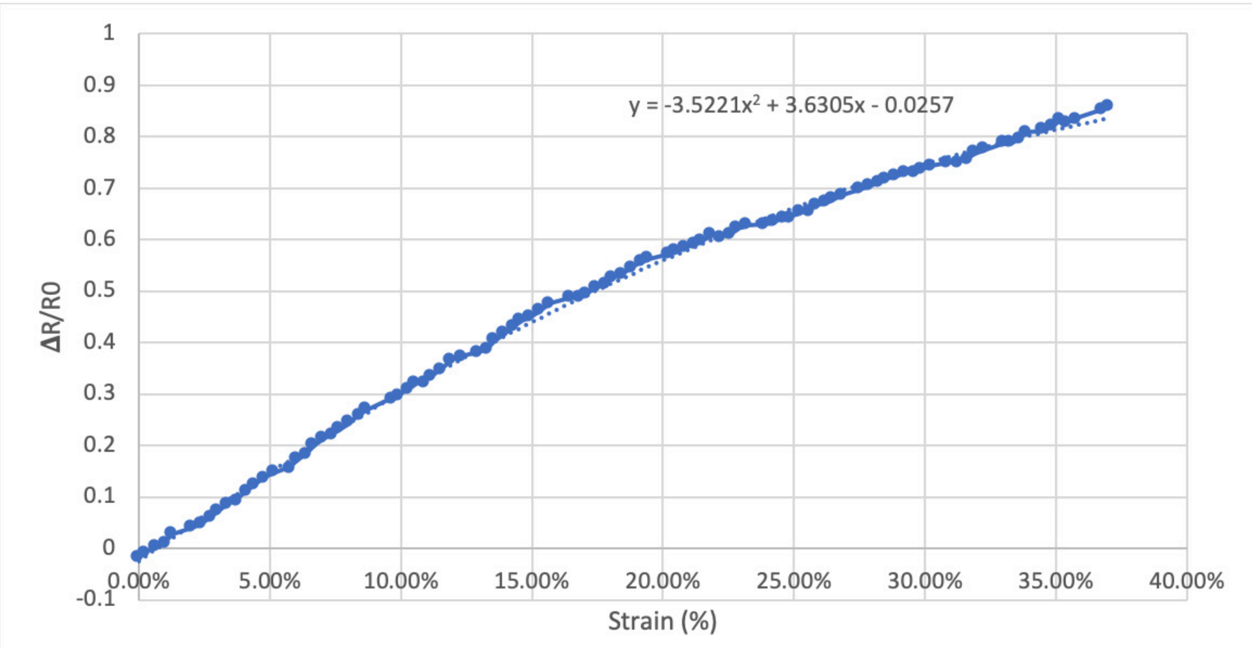


Figure 5.11 | Working Range

Transitioning from the controlled testing environment of the LETT to a sensor that would work on an actual elbow joint was done in several stages. First, the sensor was attached to the joint and connected to a multimeter. The elbow was moved from 0 (completely outstretched) to 130 degrees. Every 10 degrees a picture was taken to later read of the data and see in what range the sensor was working. This sample had 4 lines of stitching, all 8 cm in length. (Figure 5.11)

The sensor was then connected to the Arduino and the graphs shown in Figure 5.13 and 5.14 are the first and second test using a real elbow, respectively myself and someone outside of the research. The first still with the different electrical components in a temporary breadboard, and the second with all electronics permanently fixed.

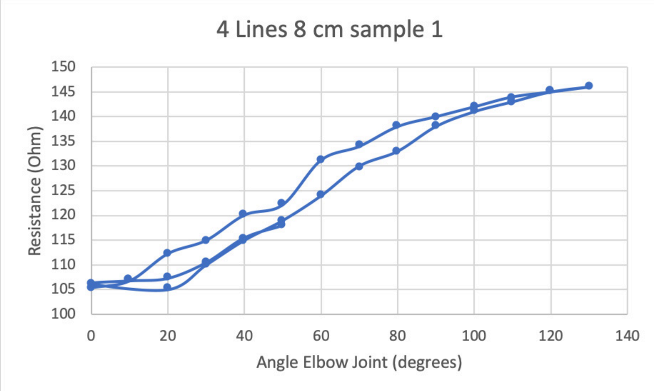


Figure 5.12 | Four lines of stiching analog measurements

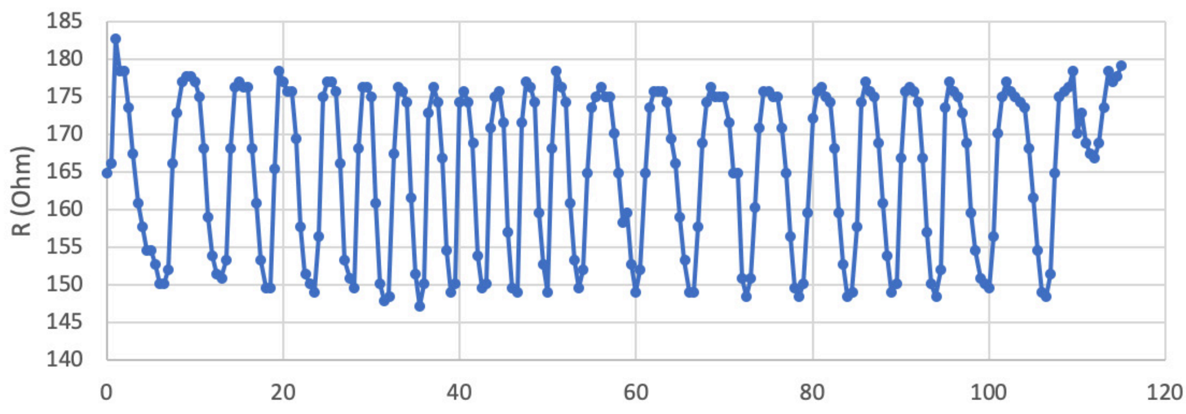


Figure 5.13 | First Test with Prototype (on Self)

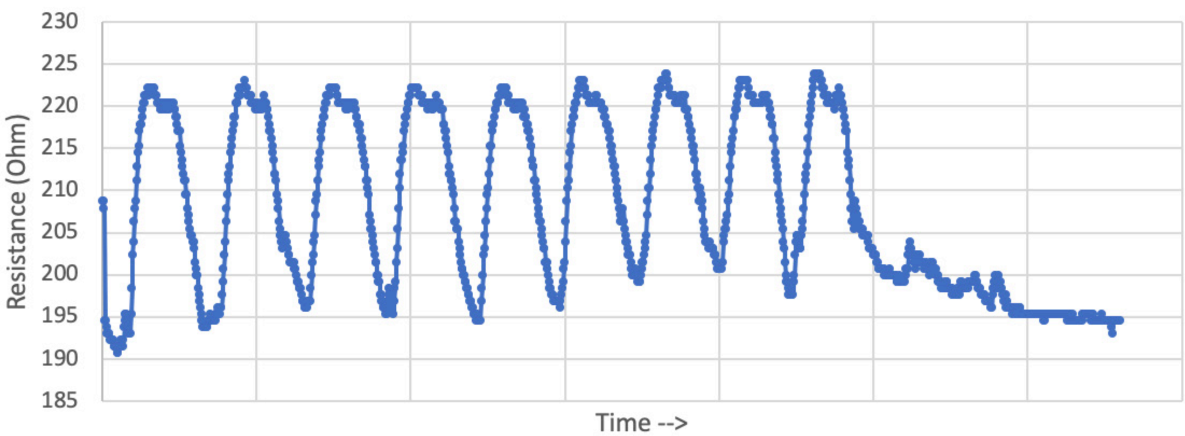
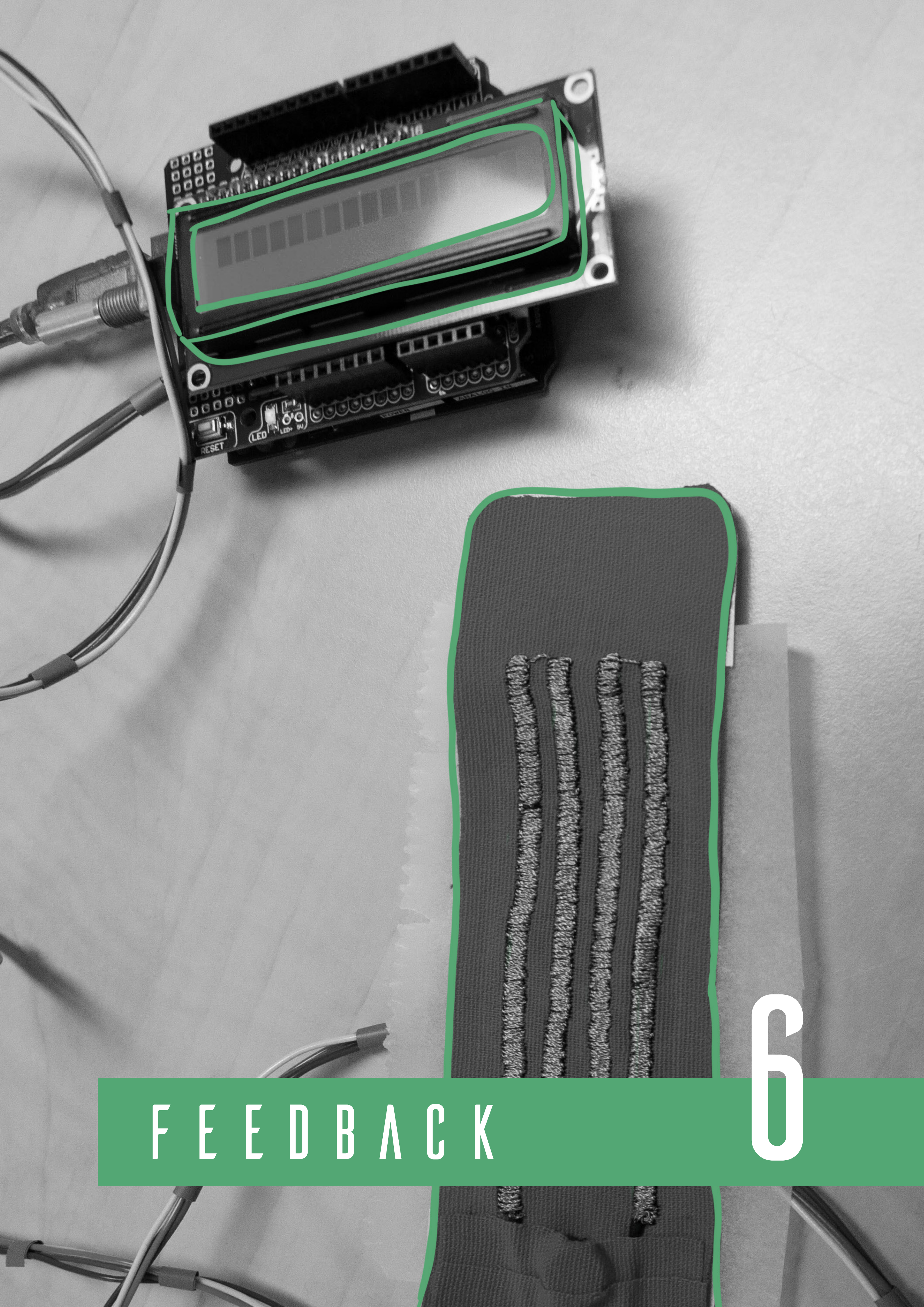


Figure 5.14 | Second Test with Prototype (on other tester)



6 FEEDBACK

With the gathered data from the sensor we have a good overview of the motion that is being performed by the user. For the final product we want to know what information we want to communicate to the user and how. An overview was made of the available information that can be extracted from the raw data in the next section.
The remaining part of this chapter, different feedback methods will be discussed and selected for further development.

FEEDBACK POINTS 6.1

The raw data received from the sensor is a measurement of the Voltage running through the sensor. As discussed earlier, this can be processed and recalculated with help of prior calibration to the angle of the joint.
This means we receive a plot of the movement in degrees of a joint over time. From this plot, we can extract the following information.

- The position of the joint at a given moment.
- The moment the user reaches the desired movement.
- The moment the user overshoots the desired movement.
- How many repetitions are performed.
- The speed with which the repetitions are performed.

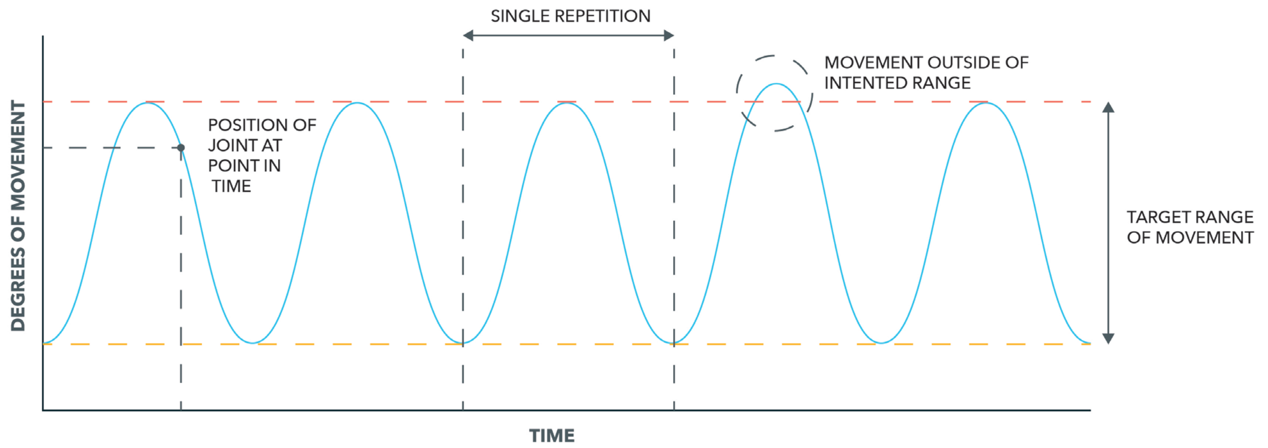


Figure 6.1 | simplified representation of sensor output

6.2 FEEDBACK OPTIONS

To relay this information to the user, it needs to be perceptible. All five senses considered, taste and smell are rejected. The feedback to these senses cannot vary fast enough and are not feasible solutions to realize within this project. This leaves vision, hearing and feeling to be utilized in the communication of the desired information to the user. Zooming in on vision, we can make a distinction in (brightness of) a light, a color change, an image being shown, or text. An auditory distinction can be made with a voice or sound. The most practical application of feeling in the project is the use of vibration.

To get a better grip on the different options and their place in this project an overview can be seen in table 6.1. Here the actuators represent different kinds of ways to give feedback to the user, as is feasible on the product itself. Incorporating a screen is left out of the scope, because if a screen is deemed necessary, a mobile device will fill that need. These are then tested to the core values of the design vision.

Not only the kind of feedback but also the source of feedback should be considered. The consideration was made to either use a mobile device already in possession of the user, or let the product itself deliver feedback queues. These are compared using the same criteria as the forms of feedback in table X.

Table 6.1 | Feedback options

	ACTUATORS	FEEDBACK ON MOVEMENT	MINIMAL DESIGN	SMART MATERIALS	INITIATE INTERACTION/ NUDGING
VISION	Screen	+ Very precise feedback possible	- extra device	- feedback not integrated	- not always visible
VISION	Color Change	+ can visualize a scale - not an exact scale	+	+	+ always present - not visible or attention grabbing
VISION	light (electro-luminescence)	+ can visualize a scale + can visualize movement - a lot of separate components and electronics	+	+	+ always present - not visible in sunlight or beneath cloting
HEARING	sound	+ can be registered without seeing the movement - is not a visible or exact scale, only feedback on one condition	- needs a speaker	- no new technology	+ will be noticeable in most situations +/- noticeable by environment of user - intrusive
TOUCH	movement (vibration)	+ can be registered without seeing the movement - is not visible or exact scale	+	+	+/- private
	mobile phone	+ can visualize a scale and addditional information	+/-	only sensors	+ almost always with user - initiates a lot of interactions, how does it not blend in with all the other notifications
	product	+ can viusalize a scale and additional information	-	only sensors	+ makes the nudge more "special" - has to be carried around or be in the right place

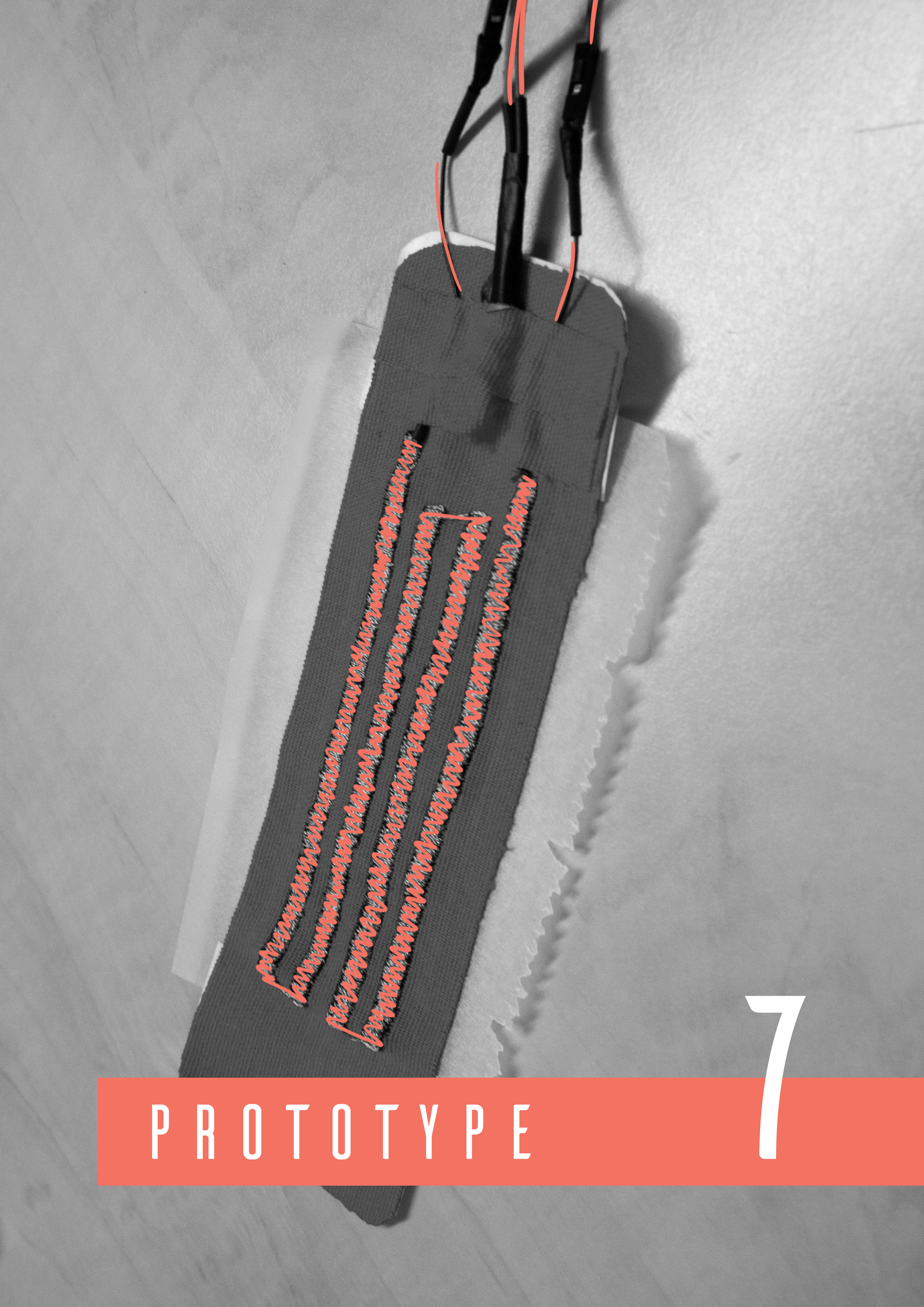
6.3 CONCLUSIONS

There are two moments during the use of the product where we want to communicate something to the user. Firstly, we want to make sure they start doing their exercise, and second, we want to give them feedback on their movement during the exercise.
To nudge people and remind them about the exercises, we want to create a unique trigger that does not blend into the sensory overload of all the notifications and triggers people receive during the day. This means sending a notification using a mobile phone is not ideal. Also it being too intrusive by using sound or vision could make the user turn away from the product, so exploring tactile feedback in this situation will be a very interesting direction.

Using the parameters we established in the design vision and the technical options available, we can make a selection of feedback options we further want to explore during the exercise itself.
Most exercise supporting applications have a sound or voice based motivational system, so we want to see if something else could be equally or maybe more efficient. For this project, we want to explore the options that are not sound based.
Also we want to make a minimal design, which means adding a speaker to the product would be an extra large component.

Using tactile feedback is a big opportunity, because we are already placing a sensor at the joint, so we could easily add a small vibration motor. This hypothetically could also link the feedback more to the movement, because it is locally giving a direct response. The downside of tactile feedback is not being able to register small changes in the intensity of the feedback and that the feedback is very one-dimensional, meaning only a limited amount of information can be transmitted.

Visual feedback on the contrary, has very diverse possibilities of transmitting different types of information. Since this will give more insight and more possibilities to support the user during the exercises a mobile phone would be a great addition in this context, when the user has already started to do their exercises.



PROTOTYPE 7

A working prototype was realized to investigate the working of the sensor over time and the usability of the different types of feedback that are possible with the gathered data.

7.1 REQUIREMENTS

Previously we established screen based visuals and a vibration based tactile feedback to be most fitted in our context. Tactile feedback in this form has the advantage of being located on the joint and therefore connected to the user and movement, but cannot indicate with enough precision exact data on the movement and exercise.

During the user tests with this prototype we want to explore two different scenarios with different combinations of information given communicated using the two selected types of feedback.

7.1.1 Tactile Feedback

Since subtle differences in tactile feedback are not noticeable on every part of the body, but switching the feedback on and off can be felt, this source of feedback was used to indicate a moment, or certain angle of the joint, to the user. In the different scenarios the tactile feedback needs to indicate either the end of the movement, or the point where the user is moving outside of this movement. The first gives a clear indication on when to reverse the movement, but therefore gives a feedback signal two times every repetition in this scenario. The second only gives off a signal when the joint exceeds the intended movement angles.

Subtle changes are difficult to notice, but a substantial change in both intensity and length of the signal can be observed. For both situations a longer and more intense signal was produced to indicate the end of the exercise.

Visual Feedback 7.1.2

Communication using the visual cues on a screen can transfer all the gathered information on the movement to the user. The goal is not to overload the user with data and therefore make the exercise more mentally demanding. In the first scenario a sliding scale is shown to indicate the angle of the joint and the repetitions already completed by the user. The second scenario will have both these cues, but added to that the angle of the joint displayed in numbers. Also a “end of exercise” message was added.

7.2 COMPONENTS

To realize the prototype, a arduino uno was used with a protoshield, a LCD screen and a small vibration cell connected to the sensor. All the connections and resistors are soldered to the protoshield. The sensor is connected to a wire using Electric paint and a pin-connector makes it possible to switch sensors between tests.
To connect the LCD screen to the prototype the LiquidCrystal library was installed and to make the sliding scale possible, LcdBargraph was used.

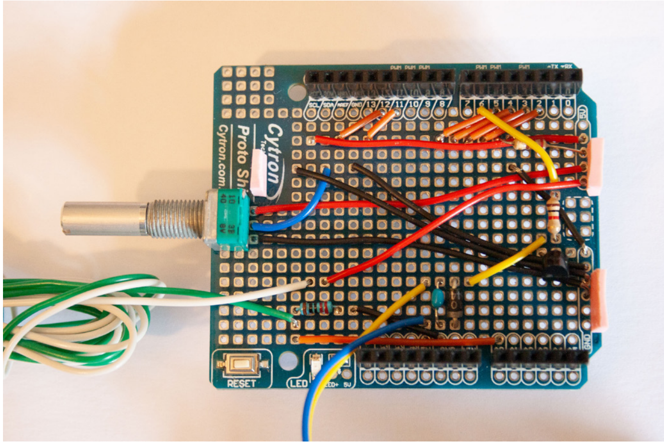


Figure 7.1 | Protoshield with Prototype components, without the screen.

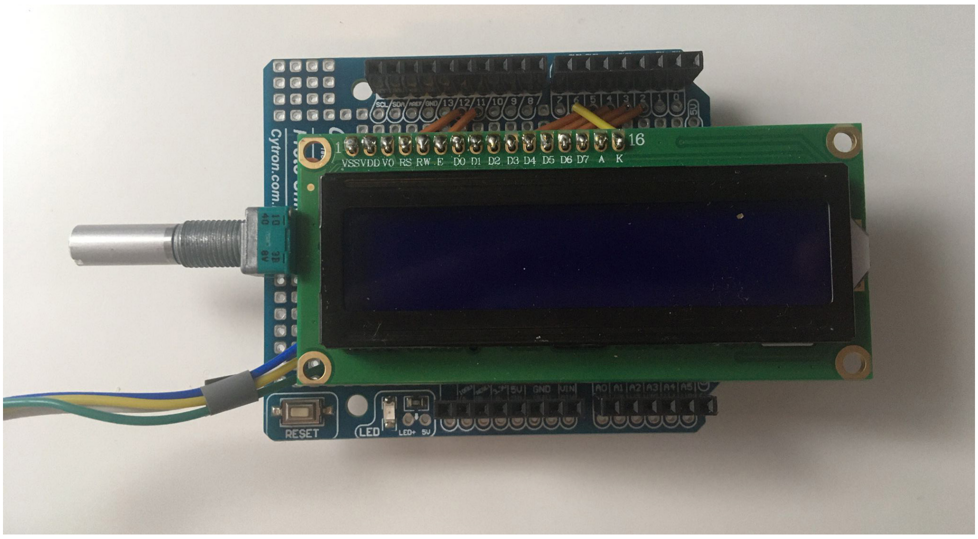


Figure 7.2 | Protoshield with Prototype components.

The protoshield with the circuit to control the vibration motor.

VM1 - Resistor 1kΩ
VM2 - 2N222 NPN Transistor
VM3 - 1N4001 Diode
VM4 - 0.1µF Ceramic Capacitor
VM5 - Vibration Cell

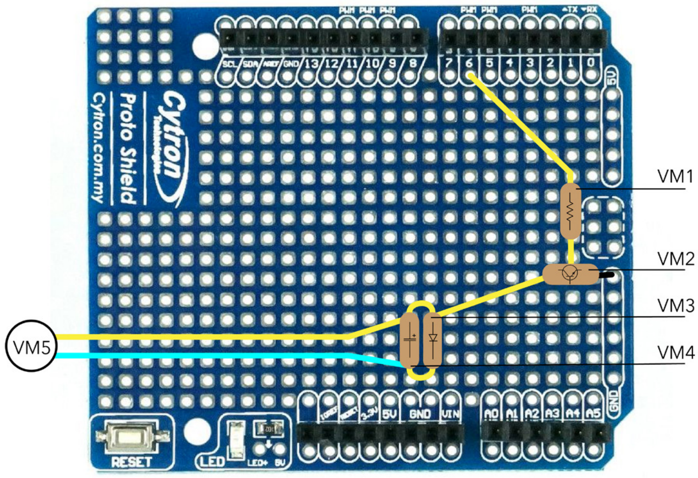


Figure 7.3 | Vibration Motor Circuit

The protoshield with the circuit to collect data from the Textile Strain Sensor.

TS1 - Resistor 220Ω
TS2 - Textile Strain Sensor

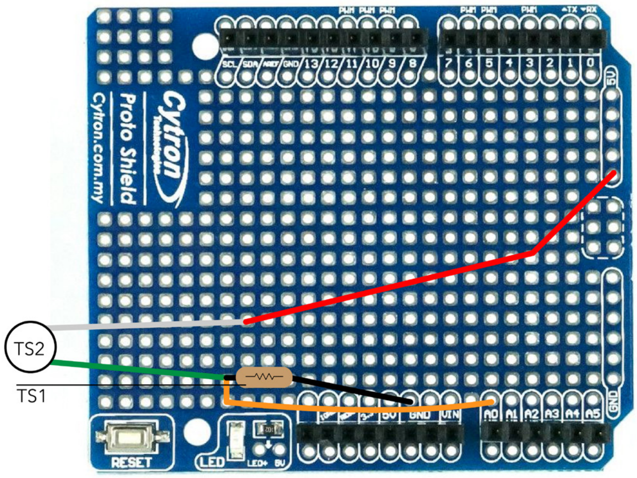


Figure 7.4 | Textile Strain Sensor Circuit

The protoshield with the circuit to control the LCD screen

SC1 - Resistor 220Ω
SC2 - LCD screen 16x2
SC3 - Potentiometer 10kΩ

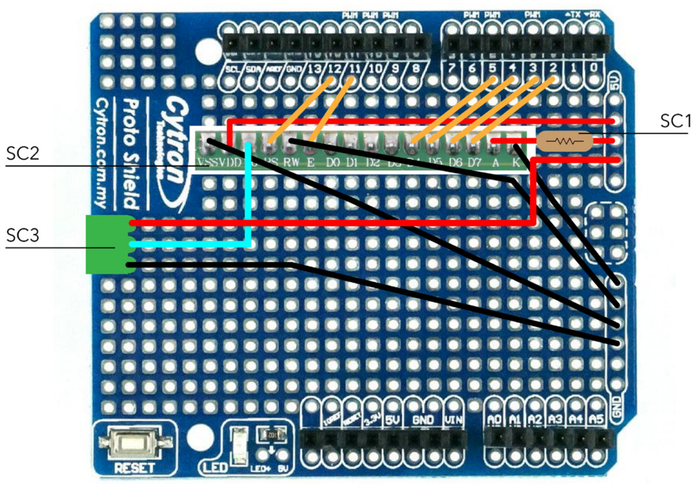


Figure 7.5 | LCD Screen Circuit

8 EVALUATION

Following the construction of the prototype and the sensor reaching stable output in a controlled environment, the product is ready to be tested with people. Usertesting allows us to research two main topics. Firstly, if the sensor gives accurate readings during use and if the sensor changes over the course of performing different exercises. Secondly, different ways of communicating the information gathered by the sensor to the user can be evaluated. The following Research Questions represent these topics and will be our main focus for this evaluation.

Q1. Does the sensor output change after repeated use?

Q2. Does the perceived accuracy of the user translate to the measured accuracy by the sensors?

Q3. What feedback does the user experience as helpful?

Sensor accuracy over time
Before the exercises, a calibration exercise was performed. After executing the whole test, the user was asked to perform the same calibration exercise. This way an indication can be given as to how quickly the sensor will start to vary from its initial values.

Perceived Accuracy
The user was asked with every exercise how they experienced their performance. This can be compared to the data measured by the sensor to see if a correlation can be observed.

Helpful feedback
"Helpful" can be interpreted in many ways. For this test, we looked back at our design vision and specified our first research question to the following sub-questions:

Q3.1. Does the product motivate the user to perform exercises?

Q3.2 Does the user feel supported during exercises?

Q3.3 Does the product influence the confidence of the user in performing this exercise?

METHOD 8.1

We conducted a 3x1 within subject (N=6) prototype evaluation, comparing the experience and accuracy of the participant with the prototypes.

Measures 8.1.1

Before the participants started their test, they were asked to fill in a general questionnaire to get a view on the demographics of our research. Beside the age and gender we also asked if they were left or right handed and if they had any restrictions in the movement of their elbow.

During the usertest we asked after every set of exercises what the user experienced during the exercises. The user was asked to rate the following statements using a 7 point likert scale, ranging from "totally disagree" (1) to "totally agree" (7) with 4 representing "neutral".

- I performed the exercise exactly as intended.
- I was confident in what I needed to do.
- I knew when I was finished with the exercises.
- I was within 5 degrees of my goal with most of my exercises.

Using the feedback providing prototypes, the following statement was added to this questionnaire.

- I feel like the product provided accurate feedback on my movement.

Also a more elaborate questionnaire was added in these instances where every type of feedback was rated using a 7 point likert scale on how informative, motivating and confidence boosting they were experienced.

After the three sets of exercises, a small conversation was held to discuss some final thoughts about the different prototypes.

8.1.2 Materials

Every participant performed three sets of exercises, while using a different prototype for every set.

Prototype A
While performing the exercise a bar was shown on the screen showing their arm angle at that moment. The bar being empty when the arm was fully stretched and being full at a 90 degrees bend of the elbow joint. The screen also showed the number of repetitions as a numeric value. The vibration motor on the sensor gave a short feedback when the user reached the end of the motion and a longer feedback at the end of the exercise.

Prototype B
This prototype shows the same information on the screen as A, with the addition of the numeric value of the arm angle and a message at the end of the exercise. The vibration motor now only signals the user with a short feedback when they are five or more degrees outside the range of the intended exercise, so if they make a "mistake".

Prototype C
As a control test, the "C" prototype showed no feedback on the screen and gave no signal using the vibration motor.

Task 8.1.3

After getting the sensor secured to their elbow, we did a calibration test to set up the prototype for use. For every prototype, the user was asked to perform the same exercise. This consisted of moving the elbow joint from a 20 degrees position to a 70 degrees position and back. We deliberately gave them a range that was harder to determine by eye -than for example 0 to 45 degrees- so the sensor could give useful feedback, this to also simulate feedback of joint-movement that can not be seen by the user. They were asked to repeat this 13 times. We considered this amount high enough to introduce a chance of miscounting by the user, but not too long to needlessly extend the usertest.
Ending the tasks, another calibration test was performed to give an indication of the change of output value of the sensor after use.

8.1.4 **Procedure**

The testing was conducted in variable locations. The order of the three prototypes -A,B, and C- was randomized for the different participants to minimize the users getting better at the task at hand influencing the data.

A short overview of the steps taken every test:

Preparation. Short introduction to the project and goal of the test. Opportunity for the participant to give permission to use data, photo and video materials in this research. Questionnaire demographics.

Sensor calibration. Adhering the sensor to the participant's elbow. Calibrating the sensor by noting the value output received with the elbow in the 0, 30, 60, and 90 degrees position. Inputting the 0 and 90 degrees value into the code to calibrate the prototype.

Prototypes. Performing the exercise with the first prototype. Answering a questionnaire about their experience with the first prototype. Repeat for the second and third prototype. Prototypes were presented in random order.

Wrap-up. Checking the sensor by noting the value output received with the elbow in the 0, 30, 60, and 90 degrees position, as during the calibration. A short conversation on which prototype the user preferred and if they have any comments on the test or product. Removing the sensor from the participant's elbow.

To be able to reuse the sensor, we used Mueller Tuffner Pre-Tape spray to make sure the sensor still adhered proficiently after repeated use. To make sure all the residue was removed from the participant's skin we used Mueller Tape & Tuffner Remover.

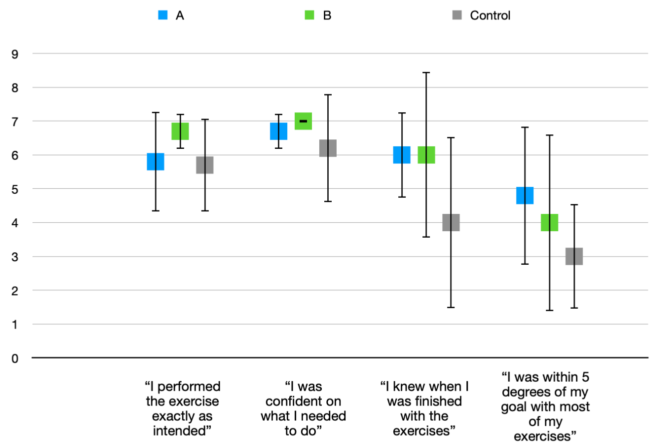
Participants 8.1.5

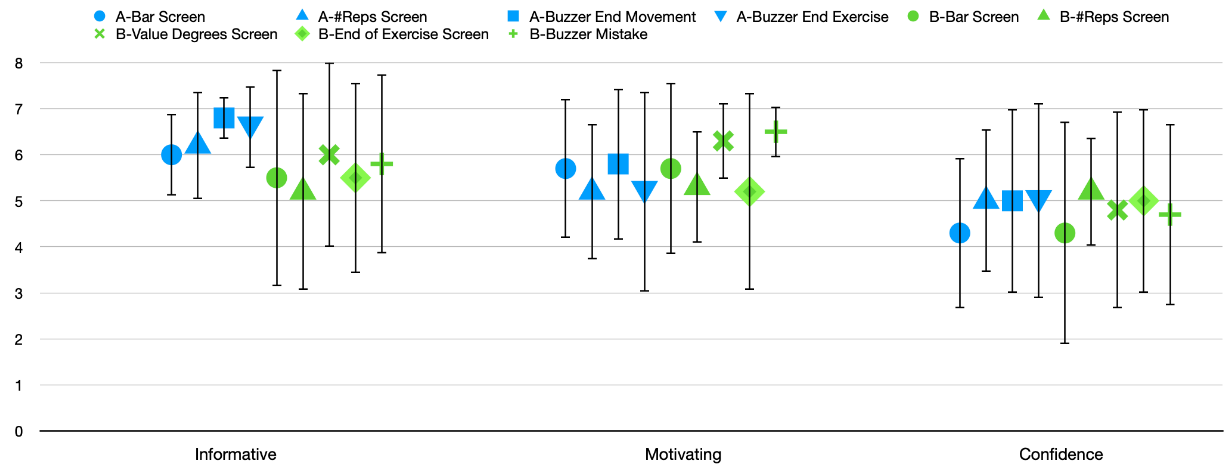
All tests were performed with six participants. Below an overview with demographic information can be found.

	AGE	GENDER	LEFT OR RIGHT HANDED	ELBOW RESTRICTIONS
1	28	F	R	NO
2	30	M	L	NO
3	29	M	R	NO
4	28	M	R	NO
5	25	F	R	NO
6	27	M	R	NO

8.2 RESULTS

We collected all the answers to the different questionnaires during the usertest, the calibration before and after testing, and the sensor output values during the use of all three prototypes. All questionnaire data on the experience of the users with the different prototypes was combined, the means and standard deviations were calculated and can be found in Fig. XX and Fig. XX.



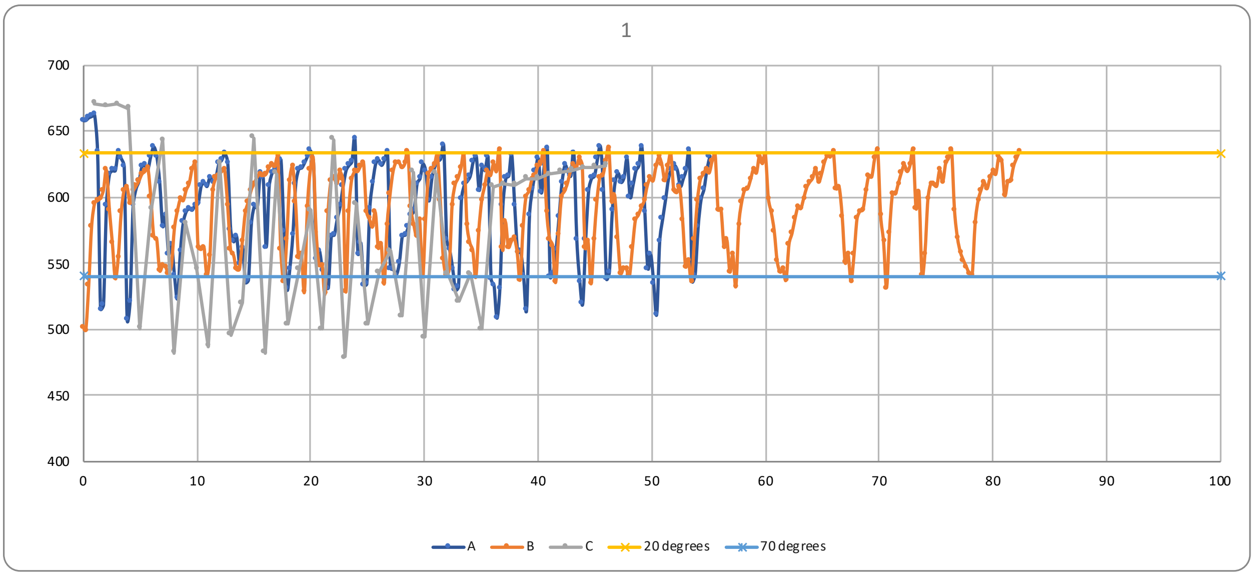


For every participant the sensor values were plotted together adding reference lines for the intended range of the exercise.

The measured output value of the prototypes is a number between 0 and 1023. This range represents the range of Voltage from 0 to 5 volt the arduino can measure. A value of 0 represents 0 Volt, where a value of 1023 represents 5 volt. This Voltage is combined with the value of the constant resistor used, like discussed in the previous chapter, to calculate the resistance of the sensor at a given moment.

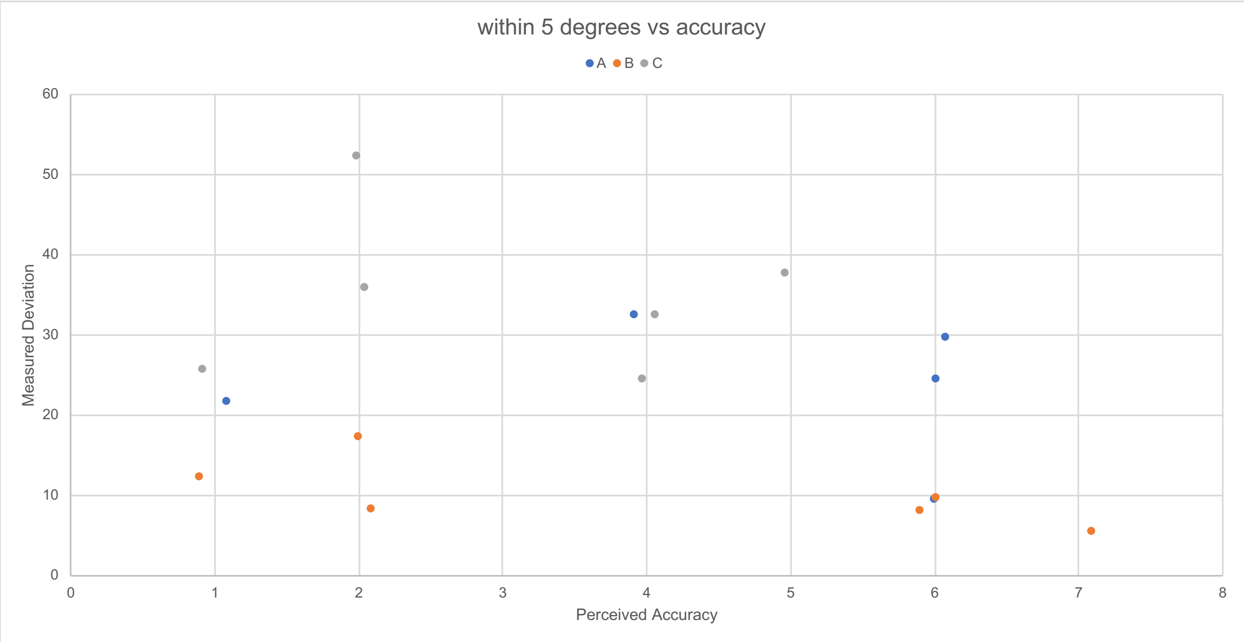
A high measured voltage means a lower resistance and a lower measured voltage means a higher resistance. A lower resistance indicated less strain, meaning a smaller arm angle -where a fully stretched arm is defined as 0 degrees and a bend arm at 90 degrees-, where a higher resistance indicates more strain on the sensor and a bigger arm angle. All graphs will show the raw measured value of the prototype. A higher raw value represents a smaller arm angle. The 20 and 70 degree values are represented in the graphs for reference.

For every participant the range that represents the arm movement from 0 to 90 degrees is slightly different, but averages out at 155, which means one degree is approximately represented by 1,72.

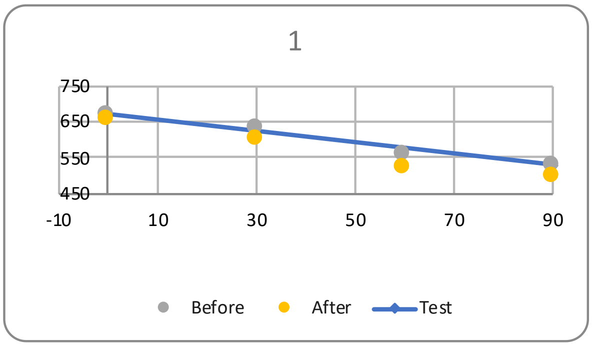


To compare the accuracy of the users while testing the different prototypes, all minima and maxima were collected for every repetition. This was done by color grading the values and hand selecting the high and low values, if the peak was not easily definable, the graph was consulted to determine the correct datapoint. These were compared with the intended values -of 20 and 70 degrees- to determine the difference.

These differences were combined per prototype, per user to calculate the mean.
These points that represent the actual accuracy of the participants, are plotted against the perceived accuracy. The perceived accuracy is determined by the answers to the question "I was within 5 degrees of my goal with most of my exercises".



Two different sensors were used during testing. For both, the output values for a 0, 30, 60 and 90 degrees elbow joint angle were determined before and after testing. Since the sensor is almost linear, only the 0 and 90 degrees values were used by the prototype to determine the output of the sensor, which is visualized with a line in figure XX. When we take the average of the difference for every point for every participant, we get a value of 15,5. The average range from 0 to 90 degrees over all participants is 155.



8.3 CONCLUSIONS

We started this chapter with three questions that we tried to answer by conducting a usertest with a small sample of participants. They centered around the technical performance of the sensor, the accuracy of the participants while using the different prototypes and the experience of the user.

8.3.1 Sensor output

The difference in measured data before and after the test was 15,5, which is 10% of the data points from 0 to 90 degrees. Remarkable is not all sensors changed in the same direction after use and the biggest change was seen in the shape of the curve. Some gave a higher resistance, while others read a lower one. If we only look at the 0 and 90 degrees values it is only 12, making it only a 7,7% deviation. A footnote does have to be made on the length of the test. The test only took a few minutes and consisted of a few small exercises, making the findings not defining for longer usage.

The technical performance of the sensor was, in the first place, sufficient to deliver accurate data to the product so feedback could be generated on the movement. Our hypothesis of the sensor getting stretched less because of the adherence to the skin by the kinesiotape aligns with the results.

Movement accuracy 8.3.2

All participants recorded the highest accuracy when using the "B" prototype. Using the "A" prototype also saw an improvement when compared with the Control test. The perceived accuracy went up for both prototypes versus the control test.

A hypothesis for the cause of this discrepancy between perceived accuracy and measured accuracy can be that prototype "B" showed the degrees of their movement in numbers, so it made it easier for the user to be more precise, but also made them more aware of errors they were making. This leads to lower estimations of their own performance, while they actually have a very high accuracy.

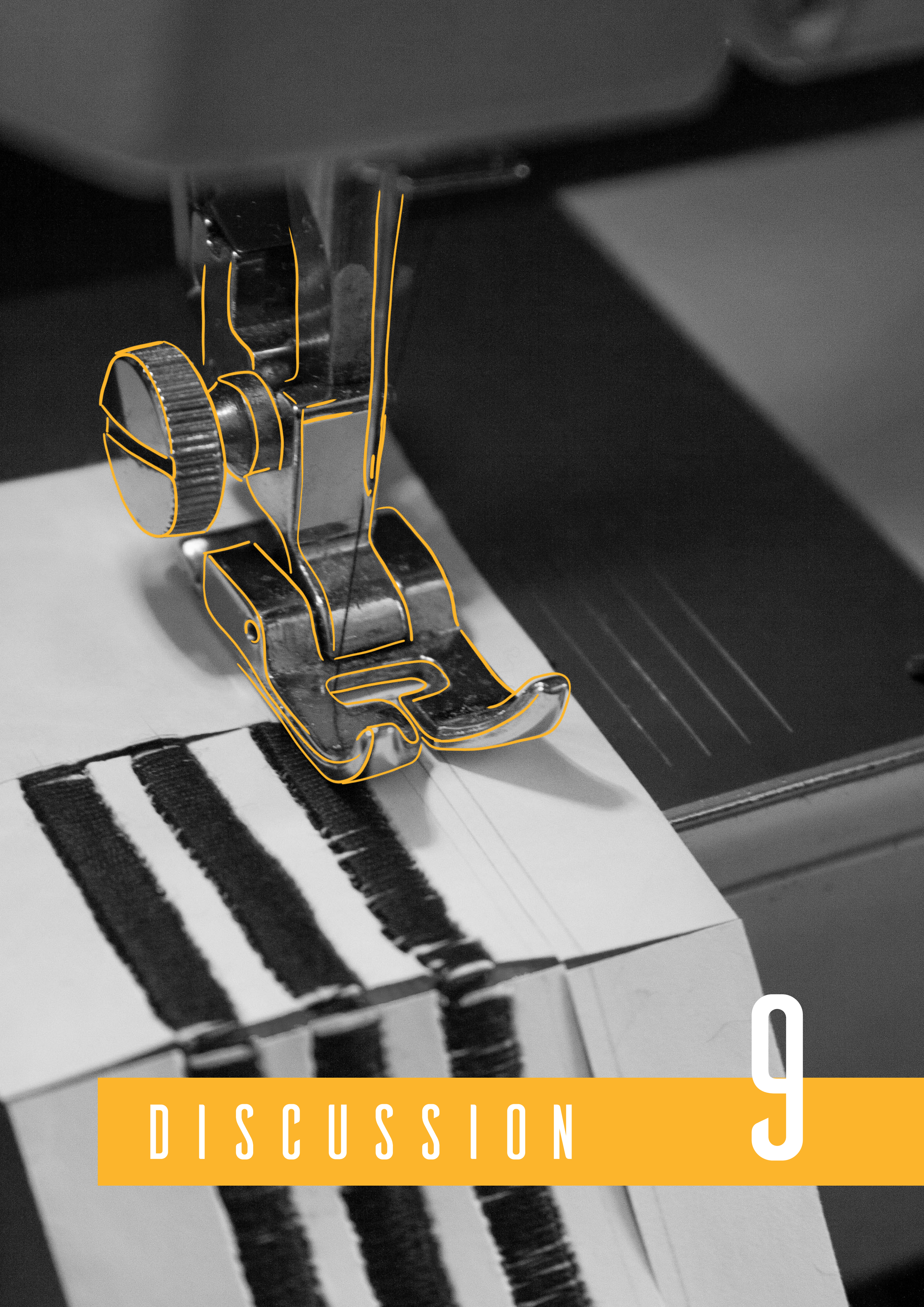
8.3.3 **Helpful feedback**

We split up the term helpful in three parts that we will interpret separately.

Was it informative?
The biggest difference between the two prototypes is found here. Prototype "A" gets consistent higher scores on all of its feedback options with a lower deviation. Also the feedback options that were the same for both prototypes are rated higher. This can be explained by the presence of more, and arguably more accurate, ways of feedback in the "B" prototype.
If we split up the visual and tactile feedback, we see the bar on the screen and the amount of reps were considered very informative. When in prototype "B" the actual value of the current armangle was added, the previous two were found less informative, since a more accurate source was added.
When looking at the tactile feedback, the buzzer that indicated a mistake was experienced as less informative than the buzzer at the end of the movement and at the end of the exercise.

Was it motivating?
The evaluation of the kinds of feedback in this context gave us two feedback options that were both rated higher and had a smaller deviation than the other options. On the screen the actual value in degrees of the arm motivated the participants to be as precise as possible when executing their motion. The existence of the buzzer when the movement was overshot by 5 degrees or more added to this motivation of wanting to execute the movement as precisely as possible and not get the "punishment". This also showed in the accuracy with which the participant executed the movements. Using the "B" prototype, they were consistently more precise.

Did it give me confidence?
Answering this question the participants rated all the feedback options roughly equal to each other. The one thing that is noticeable is that for both prototypes the bar value scored lower than all the other kinds of feedback. Since there were no indicators accompanying the bar graph to give extra information on the data that was shown in the graph, participants did not know what to look for in this graph, thus making them less confident in their actions.



9 DISCUSSION

We investigated psychological barriers patients experience during the execution of their physical rehabilitation at home. To increase the chance that their task will be completed, there are roughly two possible paths to take. The first is to make the task easier, the second to make the user more motivated. Giving feedback on the movement using the input from a textile strain sensor proved to cause both. With the feedback, people have to think less about the exercise and don't need to keep track of the amount of repetitions. Having a small simple task to obtain that feels almost like a game, tracking progress, and the use of a novel product adds to their motivation.

The textile strain sensor in this context needs to (1) be accurate enough to give useful feedback to the user, (2) needs to be stable over time and (3) usable by the patient on their own without the help of a physical therapist. Within the restraints of the prototype the step increments were on average a little less than 0,6 degrees, which means an accurate enough representation of the movement of the (elbow) joint in this context. Using the kinesiotape means the stability of the substrate is directly correlated with the stability of skin, since it is adhered to it. Skin has a very high flexibility and ability to recover to its original state. Another way the kinesio tape adds to the experience and performance of the sensor, is the need to only calibrate it once when applied, which can be done by the physical therapist at their office. This is a process that needs to be further developed so it can be repeatable and reliable every time. The calibration at the PT's office makes it easier for patients to use the product at home, since they don't have to calibrate the sensor themselves.

The ability to track your progress can be a big contributor to the motivation of a patient, but also valuable information for the physical therapist. When you have a (digital) representation of a streak, this also motivates you to continue and not let the streak be interrupted. At the start of the treatment, people tend to be more motivated because of novelty or their injury constraining them in everyday life. This can be an opportunity to get information on the preferred schedule of the patient and the moments during the day doing exercises fits into this schedule. This information can be used in further development of the sensor to initiate interaction by the product at appropriate times.

LIMITATIONS AND OPPORTUNITIES 9.1

In this section, we will discuss the different phases of the project and their limitations, but also the opportunities that are worth exploring.

Research 9.1.1

The initial research was conducted by exploring scientific papers on the subject barriers patients experience during a physical rehabilitation trajectory and on different sources of motivation. There is a wide field of research on motivation that was not consulted during this project where other models and methods are proposed that could lead to further understanding of the motivation in this context.
To get a more varied understanding of the topic through interviews, other demographics can be considered. The participants to the interviews in this project were all female, all played a teamsport at a relatively high level, and

were between the ages of 20 and 40. A variation on all these topics can add to the richness of the data.
Combining the different theories into what we called the "doing-threshold" gave valuable insights into the current situation and the possible effects different interventions could have on the motivation.

9.1.2 Textile Strain Sensor Development

During the creation of the textile strain sensor, we made use of store bought tape and a domestic sewing machine. Even with this starting point, a stable sensor was created that could measure the angle of the joint accurately. If a new sensor would be developed, it would be advised to create an alternate production process where the sensor is first stitched onto the fabric and later an adhesive layer added, so distortions in the sensor due to the removal of the paper backing will be eliminated and a more consistent product achieved. If we want to reuse the sensor, another option would be to look into separating the adhesive from the tape and changing only the adhesive for repeated use.

9.1.3 Prototype

The current prototype is connected to the arduino with physical wires. A next step would be to transfer the data wirelessly to a device. This way there will be more feedback options using a full color and bigger screen. The look and feel of the feedback application could also add or subtract from the experienced motivation and resulting exercise adherence. Having a wireless device will also add to the freedom of movement, both perceived and actual, of the patient and the joint.

Since the sensor is attached to skin, the prediction is that the substrate won't stretch permanently over a longer period of time. We cannot be certain of this without testing it in the real world. How daily wear and tear impacts the sensor, both stretching the substrate and maybe damaging the conductive threads could lead to new insights and ways to improve the product.

Tracking the movement of the elbow joint with the current prototype and providing feedback to assist the user during the performance of their exercise was successful. If we would apply the same prototype to other joints, we predict the results can vary. The elbow joint has a high range of motion, being able to bend about 140 degrees. It is also a hinge joint, which means it only moves in one direction. The knee joint is very similar, with a slightly wider range of motion, but also the hinge property. The same applies to the ankle, but with a smaller range of motion. We predict in this situation that the sensor will work as it does with the elbow. Other hinge joints in the body are finger (and toe) joints. For these joints, the scale of the sensor has to be reconsidered, since the joint is so much smaller. This means less conductive thread can be used and the resistance will be lower.
The remaining joints, like the hips and shoulder, are types of ball joints, which means movement in more than one direction. To use the developed sensor on these joints, the placing has to be carefully determined and the sensor adjusted to fit the range of motion and the amount of stretch the skin has at these points. It can also be considered to place two or more sensors on a joint to accurately map the desired movement.

9.1.4 **User Testing**

For testing the different kinds of feedback and having a proof of concept, the user testing done with the prototype brought us a lot of insights. It could still benefit from having a bigger sample size of participants. Mainly testing with real patients and physical therapists could make the data richer. If the prototype would be in a stage where it can be possible to give the product to someone to use over a longer period of time at home, more information could be gathered on the actual motivation the product adds to the situation.

9.1.5 **Feedback**

We chose to only use tactile and visual feedback for reasons mentioned in the “feedback” chapter. It could still be interesting to also look into the use of sounds for this purpose.

There are four other areas where opportunities arise. Firstly, we took two sets of feedback and tested those. Different combinations or additions can be made to those sets to see how different kinds of feedback interact and possibly enhance each other.

Adding a screen with more possibilities, like color and a higher resolution, will make different feedback formats possible. This means a deeper dive is possible into the digital interface. During this product the only variation was made in either using a bar or showing the data as a number.

The feedback during the exercise provided us with useful insights, but when the data is gathered, it is also possible to show this to the patient and the physical therapist. This can play a big part in motivating the patient, since showing progress over time has proven to help people develop long term habits (Rothman, 2000).

The last area of research concerning the feedback could be looking at the speed. During this research no measurement was done on how fast the movement of the joint translated into feedback by the device. The exercise performed during the user tests was not aimed on speed and the feedback was quick enough to make it feel instantaneous. There could be exercises where this could be important, although in rehabilitation the exercises are normally not of an explosive nature. This feedback speed is mostly limited by the sensor threads adjusting, making further research valuable in this area.

10 CONCLUSIONS

"Combining the context of executing rehabilitation exercises at home and the new technologies being developed in the field of smart wearables to bring the motivation patients experience in the office of the physical therapist to their home situation."

We set out to replicate the motivation felt by patients at the physical therpists' office in their own homes. After all the insights we gathered, we feel the motivating presence of another human in the room, like during the rehabilitation sessions, cannot be replicated by the addition of a product. To even out this score -and still make it over the "doing-threshold"-, what we can do is to make the exercises easier and add motivation in other ways. We make it easier -reduce mental effort- by showing what exercises need to be done, counting repetitions and sets, and taking away worries concerning the correct execution of the assignments. The presence of the tape, the excitement of using a new technology, and having the product track your progress are ways new kinds of motivations are added.
In other words, besides supporting the patient during the exercises, we not only created a new source of motivation (the product), but also a different kind of motivation.

In the field of smart wearables we opened up new possibilities. We created a very stable textile strain sensor with the use of conductive silver coated thread and kinesiotape. Adding the tape as a substrate and thereby using the elasticity of skin, the stretching of textiles over time was greatly reduced. Another benefit of using the tape as a substrate is the elimination of the need to use form fitting clothes to make the sensor work. This makes the sensor more wearable in daily situations and almost all weather conditions, which could lead to a more integrated use in daily life than a bodysuit could establish.

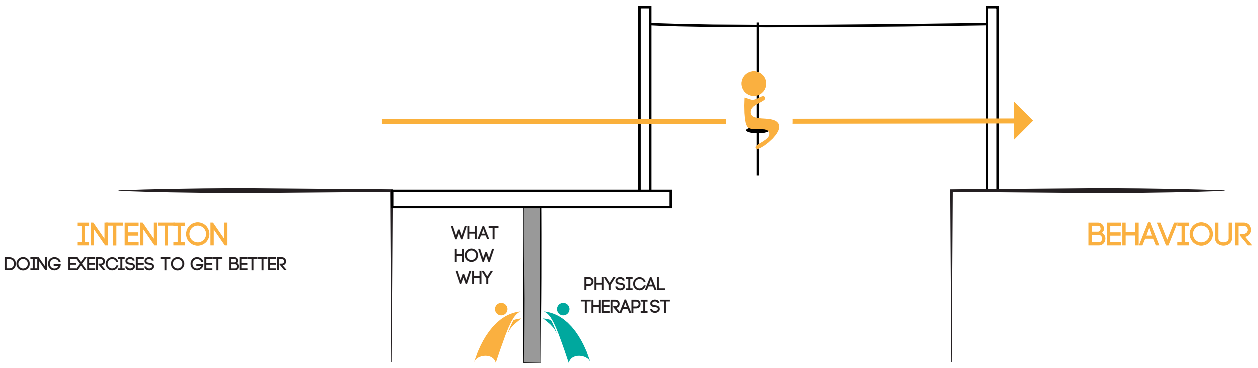
Our research was mostly conducted with patients that suffered a sports injury and physical therapists treating those injuries. This product could also translate to rehabilitation after joint surgery in a hospital setting, where it would focus more on showing the patient improvements in their range of motion or be used in learning motor skills.

According to our findings, this innovation can lead to patients being more precise in the performance of their exercises and finding the threshold to consistently execute their program lower. In the office of the physical therapist this will add a small step to the treatment, but in the long run, patients will be able to recover more quickly and won't need the help of the physical therapist less during recovery. This way, physical therapists can have an active influence, through the product, on what is happening at the patient's home, instead of only focussing on what can be done during the rehabilitation sessions.

Doing the exercises with the assistance of the product, people will have the feedback that helps them perform the exercise in the most efficient way. This does require attention and a focus on the body and the movements. Spending time focussing on the rehabilitation and the exercises can lead to feeling more in charge of their own rehabilitation process. Showing the patient that their efforts pay off using the data collected

by the sensor can show them the responsibility they have for their own health and well-being. Where in our research, physical therapists indicated that some patients expected them to fix their problems without putting in the effort, here they see their own involvement in their recovery.
In some cases, the exercises will have to be repeated for longer periods of time, or have to become a life-long practice to maintain physical fitness. The methods we researched can make the path to building a habit an easier one.

We stated that with the product, we want to build the second part of the bridge that closes the intention-behavior-gap. After our findings we can state that to close the last part of the gap, we may not need to strive for building a bridge mimicking how we got over the first part of the gap. Instead we can build a cable track to make crossing the gap effortless and even fun.



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