Designing an interactive technology to integrate at home knee-injury physiotherapy exercises into activities of daily living

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Abstract

This thesis aimed to explore how an interactive technology could be designed to improve adherence to at-home physiotherapy for knee injuries. The design approach was to integrate exercises into daily activities and objects. By identifying shortcomings and gaps in related work and generating a deeper understanding of knee injuries and treatment plans, the problem was narrowed down to mobility issues and stiff knees from staying seated for too long during the recovery process. A mat with a slider and a vibration clip was proposed to encourage knee extension and flexion during prolonged sitting. A prototype went through a user evaluation and was shown to physiotherapists for feedback. This showed that the concept seemed most promising for patients with acute knee injuries and that integration into daily activities is possible. However, further research is needed to assess long-term adherence and integration into daily routines.

Acknowledgments

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Contents

1 Introduction

Knee injuries are one of the most common sports injuries. A 2019 study into the epidemiology of sports injuries in athletes aged 14–21 showed that knee injuries occurred at a rate of 19.32% [1]. In the Netherlands, this goes up to a 23% incidence for athletes at all ages [2]. Of these injuries, 68% will get medical attention, and among them, 74% get help from a physiotherapist.

Knee injuries can be chronic or acute. While the causes and injured structures within the knee differ per injury, the general consensus is to include physiotherapy in a treatment plan to regain knee functionality. Physiotherapy includes personalised exercise regimens that are followed at a gym as well as exercises to conduct at home.

At home physiotherapy exercises, however, are not always followed rigorously. Both intrinsic and extrinsic factors can affect how well a patient adheres to their physiotherapy programme. These factors include patient-related factors, which involve self-regulation and experience; condition-related factors, such as post-operative complications; the support received from their health care system; as well as socioeconomic factors such as support from family and friends and time constraints [3].

Multiple approaches exist that attempt to motivate patients when it comes to following physiotherapy programmes. These approaches include telerehabilitation and digital platforms [4-8], such as apps and phone calls; gamified experiences [9-13] in VR, AR, and video games; and tangible interactive tools [14-19], which involve physical objects. However, these solutions have varying degrees of success, and still require the patient to add their exercises as an extra task to complete every day.

A different solution is to integrate physiotherapy exercises into the daily routines of patients instead of adding them as a separate activity. This approach has already been investigated in the case of hand rehabilitation in stroke patients [16-18]. The results have been promising. Now, the question is whether this can also apply to other domains, in this case knee injuries. By exploring this area, the approach is tested by focusing on a different part of the body and concentrating on short-term care rather than long-term care.

This leads to the following research question:

> **How can an interactive technology object of daily living be designed to improve at-home physiotherapy adherence for knee injuries?**

To answer this question, the context is explored (**chapter 2**), the current state of the art in this domain and others is investigated (**chapter 3**), and the daily routines of knee injury patients is uncovered (**chapter 4**). With this information, **chapter 5** discusses the ideation of the new interactive technology, **chapter 6** handles the prototyping and intermittent feedback, with the final prototype explained in **chapter 7**, and **chapters 8** and **9** evaluate the concept through user testing and expert opinions.

2 Context

2.1 Overview of knee injury treatment

Knee injuries are either classified as 'acute' or 'chronic.' An acute injury is caused by a single movement or impact, such as twisting or falling on the knee [20, 21]. On the other hand, a chronic injury has an 'absence of a single identifiable cause' [22]. The main cause for these injuries is a repetitive load on the joint without sufficient rest between use [23]. Injuries can have a clear cause or be idiopathic [24].

More extensive research into knee injuries, their causes, their risk factors, and the way they are treated was done in the Research Topics report preceding this thesis [25]. This section aims to provide the background knowledge required to understand the findings presented in the rest of this thesis. It covers a basic understanding of knee injuries, their treatment, as well as factors affecting physiotherapy adherence.

2.1.1 Acute injuries

An acute injury, if considered bad enough, may be treated with surgery [20, 26]. These surgeries aim to repair structures of the knee. Whether an injury is treated with surgery or non-surgically, both treatment plans usually include physiotherapy to help regain strength and functionality [20, 27-29].

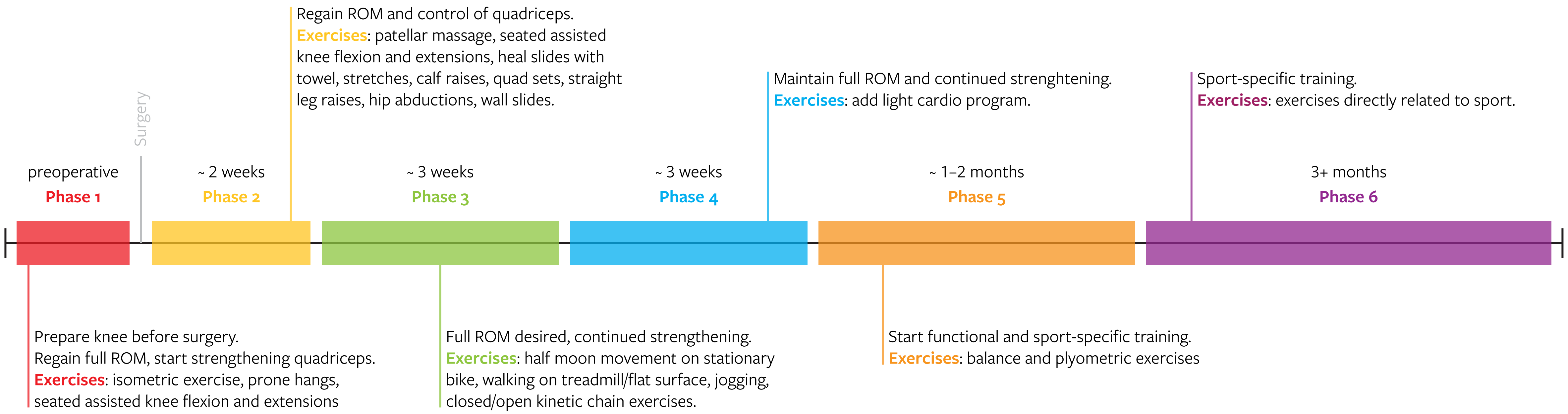


Figure 2.1 Phases of physiotherapy for ACL injuries [25].

Multiple sources describe phases of physiotherapy when dealing with an acute injury [20, 26-28, 30]. While the number of these phases and the length of the phases (as seen in **figures 2.1**, **2.2**, and **2.3**) depend on the injury as well as the source, there seems to be a general consensus in the approach. After immobilisation (if required), the first goal is to restore the range of motion of the injured knee [27, 28, 30, 31]. This is not a process that is simply done within the span of a week. It is built up over a few weeks and then requires maintenance as the patient continues progressing. Once an acceptable range of motion has been achieved, the patient begins with strength training to stabilise the knee, increasing the difficulty of these exercises over time [20, 27, 28, 30-32]. Eventually, the patient can return to sport-specific training [27].

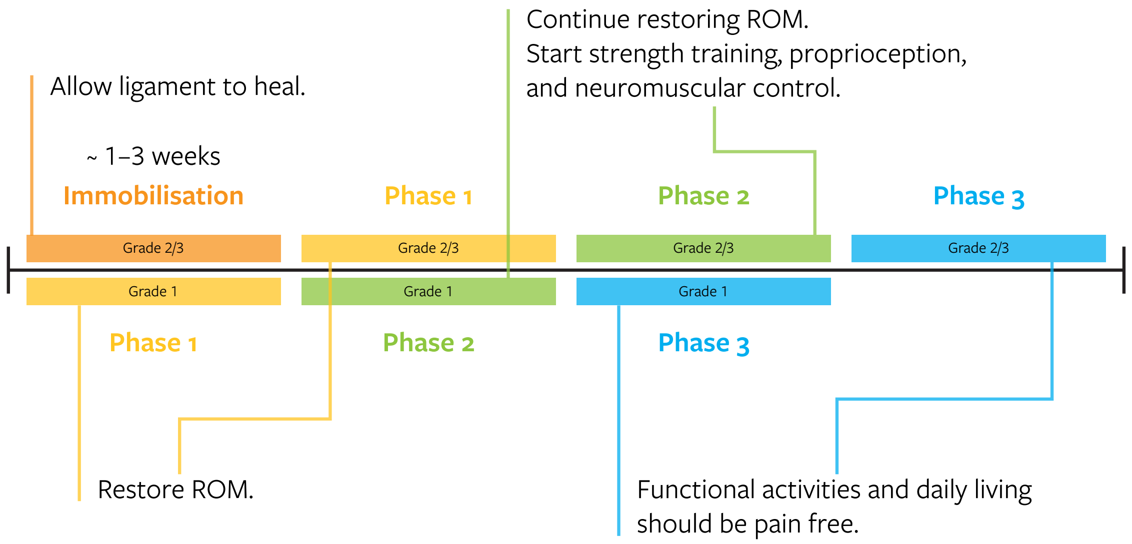


Figure 2.2 Physiotherapy treatment phases for MCL injuries. Grade 1 injuries vs grade 2 and 3 injuries [25].

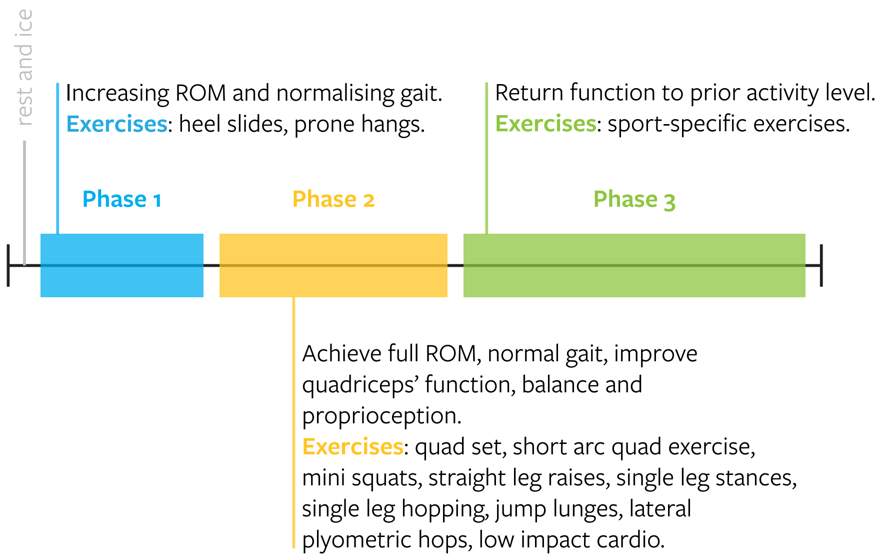


Figure 2.3 Meniscus injury physiotherapy treatment phases [25].

2.1.2 Chronic injuries

A chronic injury is usually not treated with surgery unless it has persisted for a long time and other treatment methods have failed [24, 27, 33]. There are multiple treatment methods that may be applied to chronic injuries. Often times, activity does not need to be halted, and the patient is still allowed to engage in sports as long as they are able to tolerate it [24, 27, 33]. Since the pain is caused by activity, however, plenty of rest and a lower activity level may be advised.

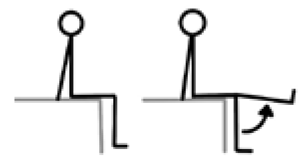
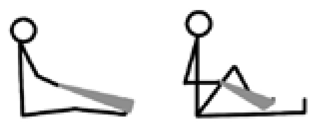
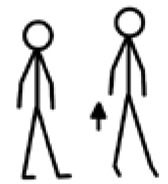
On the other hand, other chronic injuries might require a complete stop of all or specific activities for a period of time [24, 27, 33]. This is necessary when the knee must heal before activity can be restarted. Finally, injuries such as knee osteoarthritis need a long-term plan involving regular exercise [27, 34]. Each treatment method involves the use of physiotherapy to prevent the patient from worsening or prolonging their chronic injury [24, 27, 33, 34].

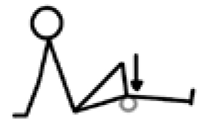
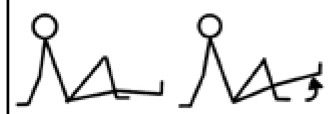
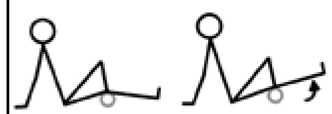
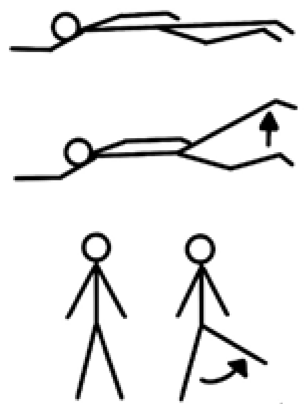
While the treatments of chronic and acute injuries differ in some ways, there is a lot of overlap in the physiotherapy exercises given to patients by physiotherapists. These exercises are described in the next section.

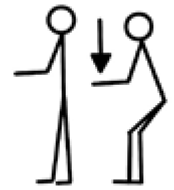
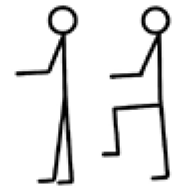
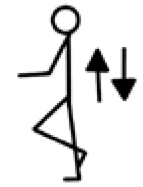
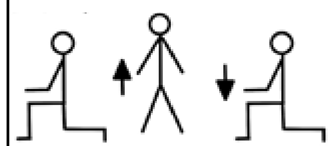
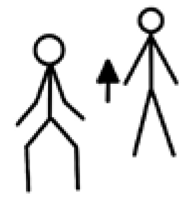
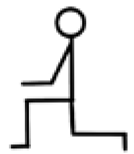
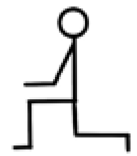
2.2 Overview of knee injury physiotherapy exercises

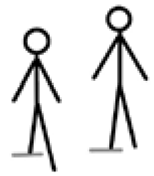
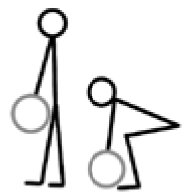
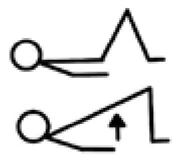
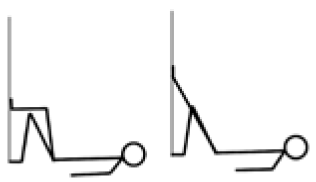
Table 2.1 lists physiotherapy exercises given to knee injury patients. This list is copied from the Research Topics report [25], which was compiled from exercises mentioned in literature [20, 24, 27, 30, 32-34] as well as an interview with a physiotherapist.

Table 2.1: List of physiotherapy exercises given to knee injury patients, taken from the Research Topics [25] report.

	Exercise	Movement	Similar daily activity	Diagram
1	Isometric exercise	Keep knee static, contract quadriceps muscle.		
2	Assisted knee flexion and extensions	Sit on a table, flex and extend knee.	While sitting, stretching legs and putting feet under chair.	
3	Heel slides with towel	Place a towel around the foot, pull on towel with arms to move foot towards hip.	Putting legs up in bed.	
4	Calf raises	Have feet flat on the floor, shoulder width apart. Raise heels slowly, keeping knees extended, and lower the heels back to the ground.	Reaching out to grab something from a cupboard.	

	Exercise	Movement	Similar daily activity	Diagram
5	Quad sets	Sitting of laying down with a small rolled-up towel underneath the knee. Non-injured leg bent with foot flat on the floor. Tighten the quadriceps by pressing knee down into towel. Hold and then rest.		
6	Straight leg raises	Lying down on back, non-injured leg at 90° angle with foot flat on the floor. Contract the quadriceps of the injured leg and lift the leg off the floor. Lower the leg back to the floor.		
7	Short arc quad exercise	Lying down on back, non-injured leg at 90° angle with foot flat on the floor. Put foam roller underneath knee of injured leg. Raise injured lower leg until knee is straight, hold for five seconds, and slowly lower back to the floor.		
8	Hip abductions	Moving the leg away from the midline of the body. Lying down: Lying down on side with bottom leg bent and top leg straight. Raise top leg up and down. Standing: Stand with legs shoulder width apart. Hold onto a chair or another stabiliser. Slowly kick leg out to the side of the body.	Side stepping, getting out of bed.	
9	Stationary bike	Cycling on a stationary bike.	Cycling	
10	Swimming			
11	Leg press	Done with a leg press machine.	Standing up. Pushing chair back.	

	Exercise	Movement	Similar daily activity	Diagram
12	Prone hangs	Lie down on a bed with the thigh supported on the bed, but the lower leg hanging off. Place a rolled-up towel underneath thigh, just above kneecap. Allow gravity to pull lower leg down and straighten out knee.		
13	Mini squats	Have feet shoulder-width apart. Bend knees and hips slightly. Hold and stand up straight again.	Sitting down.	
14	Single leg stance	Stand upright with feet together. Lift uninjured foot off the ground. Hold and maintain balance, lower foot back onto the floor.		
15	Single leg hopping	Raise uninjured foot off the floor. Jump side to side/front to back on injured leg		
16	Jump lunges	Sink into a deep lunge, jump up from the lunge, switch positions before landing. Land with other foot forward and drop into another deep lunge.		
17	Lateral plyometric hops	Feet should not be more than hip-width apart. Squat down, jump to the side and absorb the shock by squatting down.		
18	Lunges	Step one foot forward and lower body until the back knee almost touches the floor. Push back up to the starting position and put feet together.	Picking something up off the floor.	
19	Split squats	Similar to lunges. Feet stay in the same position on the floor, one foot forward, the other back, and lower body down.		

	Exercise	Movement	Similar daily activity	Diagram
20	Step down	Put one foot of affected knee on a step, and other foot off the ground. Lower the unaffected leg down and lightly touch the floor. Return to the original position.	Walking down stairs.	
21	Deadlifts*	Perpendicularly lift a bar off the ground to the same level of the hips before lowering it back down to the ground.	Picking something up off the floor.	
22	Glute bridge	The starting position is lying down on the floor with knees bent and feet flat on the ground. Arms are places by the sides. Lift the hips towards the ceiling without arching the back until the body is in a straight line. Lower the hips down to the ground.		
23	Wall slides	Lay down on the floor with the non-injured leg with the foot flat on the floor, with the toes against the wall. The injured leg is at 90° with the foot against the wall. Slide the foot up so the leg is traight and back down.		

Patient-related factors
- ↳ self-regulation
  - ↳ forgetfulness
  - ↳ psychological factors
- ↳ knowledge/experience of exercise
  - ↳ uncertainty about the benefits
  - ↳ negative perceptions of health status

Condition-related factors
- ↳ post-operative complications
  - ↳ pain
- ↳ comorbidities

Health care system
- ↳ post-operative exercise guidance
- ↳ progression of exercise
- ↳ complexity of exercise

Socioeconomic
- ↳ support from family and friends
- ↳ time constraints

Figure 2.4 Map of factors affecting exercise adherence based on Bakaa, et al. [3], with more factors added.

2.3 Physiotherapy adherence

While physiotherapy is usually prescribed as part of knee injury treatment, how effective it is depends on the patient's physiotherapy adherence. Patients who adhere to their home physiotherapy exercises have better treatment outcomes than patients who do not [35, 36]. The sports physiotherapist interviewed noted that while a poor adherence does not equate no recovery, as the body will naturally heal to some extent, patients who struggle to adhere will often experience limitations in their ability to engage in sports and other activities.

In the Research Topics report [25], barriers and facilitators affecting exercise adherence rates were categories into four groups, based on Bakaa, et al. [3]'s paper. These four categories were patient-related factors, condition-related factors, the health care system, and socioeconomic factors, as seen in **figure 2.4**.

Patient-related factors encompass internal factors including how the patient sees their own health status as well as how well they are able to self-regulate. Condition-related factors are directly related to the physical limitations of the injury, such as pain, and other ailments the patient might have. The health care system may affect adherence through the support it can offer to a patient. Finally, socioeconomic factors include whether a patient may have a support system at home and if they are able to make the time to exercise.

Picha and Howell [37] created a model intended to increase rehabilitation adherence through influencing self-efficacy (**figure 2.5**) as patients with a high self-efficacy are more likely to adhere to a home exercise program than patients with low self-efficacy. They proposed four different interventions to improve self-efficacy:

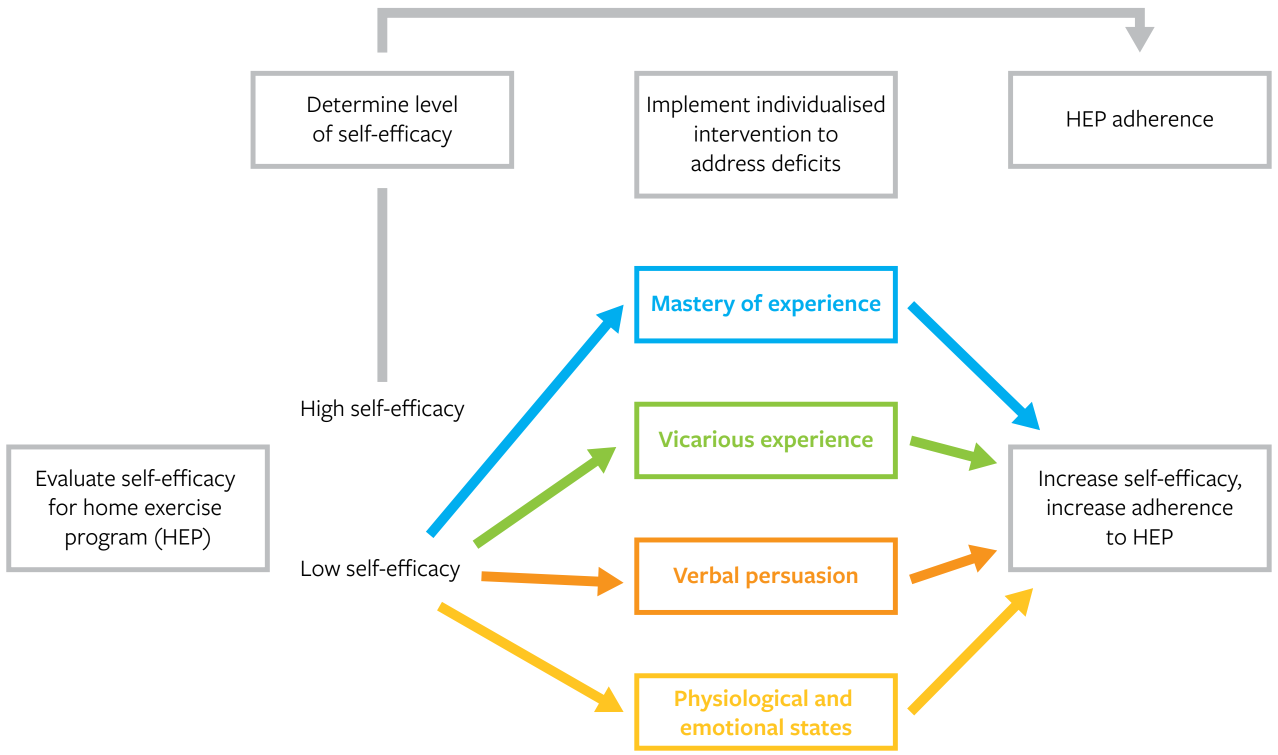


Figure 2.5 Picha and Howell [37]'s self-efficacy model to improve adherence to home exercise programmes.

mastery of experience, vicarious experience, verbal persuasion, and physiological and emotional states. These cover successes and failures in activities similar to new tasks, observing somebody else complete a task successfully, encouraging patients to do something and improving the emotional state around a task.

2.4 Chapter conclusion

Understanding the types of knee injuries and their treatments, as well as the key physiotherapy exercises involved creates an appropriate basis for the rest of the assignment. It is highly important that patients follow their treatment plans to properly restore function and prevent long-term complications. The list of physiotherapy exercises provides a source of inspiration for the ideation phase.

Additionally, the recognised barriers to physiotherapy adherence, which can come from personal, medical, and socioeconomic factors, help target the intervention. The assignment specifically targets 'self-regulation' and 'time constraints' by integrating physiotherapy into daily object and activities and making it seem less like an extra task to add onto daily routines.

3 Related work in the area of physiotherapy rehabilitation technology

Improving physiotherapy adherence is not a novel idea. This section explores existing work in the area of physiotherapy and rehabilitation not necessarily directly related to knee injuries. Three main categories of existing work were identified: tele- and digital platform supplementation, gamified experiences, and integration into daily activities, which is what this thesis also aims to do.

All discussed related work was then placed on the implicit interaction framework [38] to uncover the attentional demand and initiative of the work. This could then help discover how well existing solutions integrate into daily routines.

3.1 Tele- and digital platform rehabilitation supplementation

Tele- and digital platform supplementations aim to encourage patients through reminder systems [4] as well as providing extra information about their exercises [5-8]. These studies, however, have mixed conclusions about whether or not they improve adherence. Motivation may initially improve when giving patients reminders through phone calls, but eventually patients may start to dislike it. One main reason for this change was the dislike of needing to use the phone after already spending most of the day working on a phone or computer already [4].

In the case of digital platforms, such as apps and online platforms, different data collection methods to determine adherence rates were used, leading to mixed results. Studies basing their conclusions on qualitative data found that their solutions improved adherence [5, 8], while studies basing their findings on quantitative data found that their solution did not [6-8].

3.2 Gamified experiences

Gamification can be defined as 'the use of design characteristics for games in non-game contexts' [9] and is continuously increasing in popularity in the healthcare sector, particularly in health management [10]. The goal is to influence user behaviour through replicating the experience of playing games [10] through adding game-like elements such as rewards, competition, and achievements to otherwise relatively mundane tasks [9].

A distinguishment should be made between 'gamification,' 'games,' and 'game-based learning' (GBL). The purpose of a game is mainly to entertain while also teaching a user how to conduct a task, and GBL focuses more on the learning, which is done through playing [9]. Finally, gamification specifically targets attitudes and behaviour and aims to modify them [9], which is the most relevant for this thesis.

Within the area of gamification, related work can be further categorised into two smaller groups: motion capture, virtual reality, and augmented reality, and tangible technology.

3.2.1 Motion capture, virtual reality, and augmented reality

Technology allows us to simulate tasks and activities rather than having to do them in physical space. Using virtuality reality [11] (**figure 3.1**), mixed reality [12] (**figure 3.2**), or video games [13] (**figure 3.3**) to turn an otherwise relatively mundane exercise into something more fun has been shown to get positive reactions out of physiotherapy patients. However, once patients start to focus more on

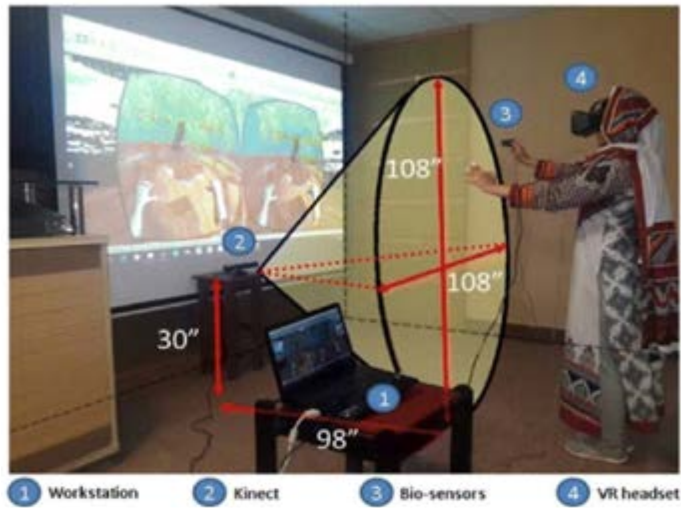


Figure 3.1 Virtual reality for physiotherapy exercises for Parkinson's disease patients. The patient picks apples from a tree at different heights [11].

Figure 3.2 Mixed reality for gait rehabilitation. The user has to pick up virtual bottles in their environment [12].

Figure 3.3 Video game for patients with neurological diseases [13].

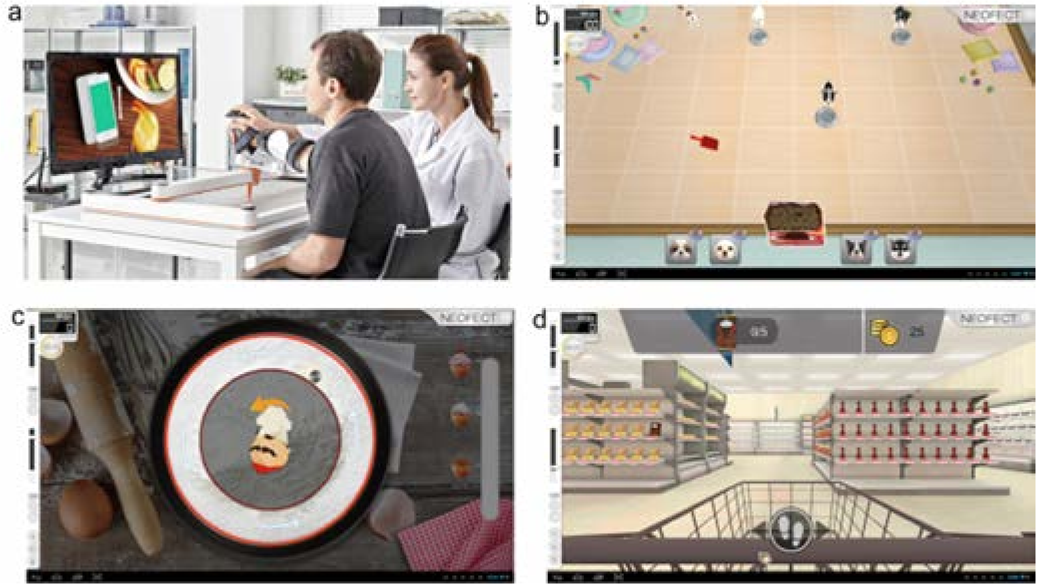


Figure 3.4 The RAPAEL Smart Board and screenshots of different games for upper-limb movements [14].

Figure 3.5 ExerTiles interactive tiles to be used during physiotherapy sessions [15].

getting a high score instead of doing an exercise correctly, gamification can also have an adverse effect [13].

3.2.2 Tangible technology

Tangible technology covers tools that modify exercises in the physical world. For example, a smart board can be used to practice gross-arm movements [14] (**figure 3.4**), or interactive tiles make a balance training session less monotonous [15] (**figure 3.5**). However, these solutions do not come without fault. Players may only play for entertainment while others might not enjoy the game at all, making it an ineffective solution for some [14], decreasing the effectiveness. Further, sometimes the solution is not perceived as any better than practices already in place [15].

3.3 Integration into daily activities

Integrating interventions into daily activities and objects is a relatively undiscovered area, but is not unheard of. Current research investigates solutions for hand rehabilitation for stroke patients. These technologies are integrated into daily objects used by patients such as cooking utensils [16] (**figure 3.6**), drink

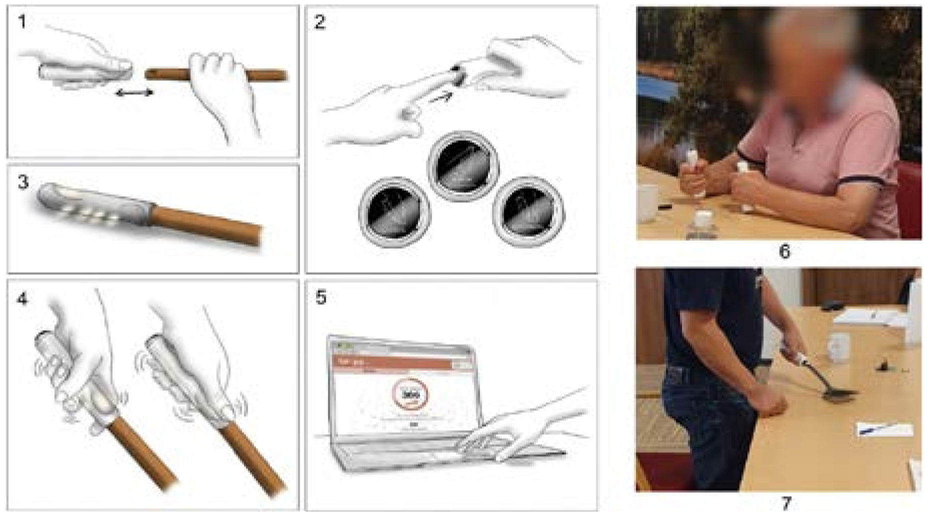


Figure 3.6 Gr!pp; a grip for cooking utensils for hand rehabilitation [16].

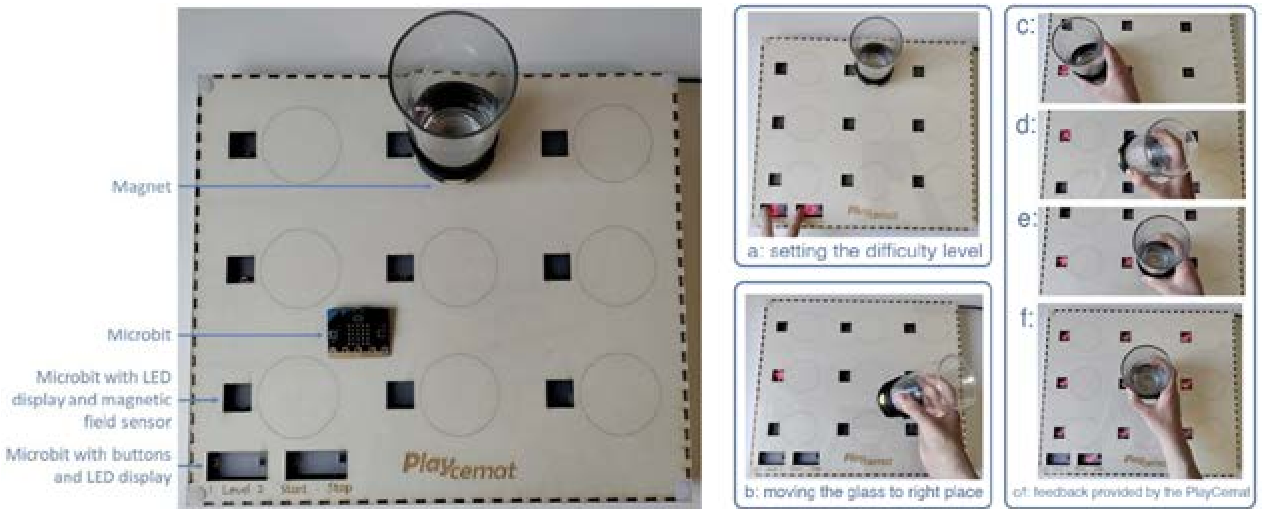


Figure 3.7 PlayCemat; using glasses as an exercise for hand rehabilitation [17].

Figure 3.8 TumbleTooth; a toothbrush that rotates as an exercise for hand rehabilitation [18].

Figure 3.9 ReSwing; a mat that is placed on a swing and trophy that tells the patient when they should do the exercise again for knee injuries [19].

containers [17] (**figure 3.7**), and toothbrushes [18] (**figure 3.8**). While these studies did not involve long-term testing to evaluate motivation and adherence, results were overall promising.

Bagalkot, et al. [19] created interactive technologies for knee patients based on exercises they were given by medical professionals, their environment, as well as activities and objects that are motivating to them. With these technologies, patients were able to track progress by, for example, seeing whether they managed to squat as far as a day earlier or whether they are stretching far enough. The technologies were integrated into daily activities and objects, such as a porch swing (**figure 3.9**), helping them become more motivated. However, these solutions were tailored very specifically to individual patients and cannot be more widely applied.

3.4 Mapping on the implicit interaction framework

The current state of research shows both promising approaches and approaches with significant challenges. Tele- and digital platform supplementations show mixed results, with some patients losing interest due to overuse of technology in daily life. Gamified experiences generate positive engagement in the short-term, but may also distract patients from properly conducting their exercises. Meanwhile, integrating rehabilitation into daily activities and object has shown promise in enhancing motivation.

To uncover where a solution for knee injuries may lay, the implicit interaction framework [38] is introduced. The implicit interaction framework places a system on a map based on attentional demand and initiative. Mapping all the existing work on this framework helps identify an area to design in.

Systems that require the attention of the user to work are in the '*foreground*', while systems that barely require the user's attention can be found in the '*background*.' The initiative plots who initiates the interaction. A '*reactive*' interaction is started by the user, as the system 'reacts', while a '*proactive*' is started by the system. The work investigated in **sections 3.1–3.3** is mapped onto this framework (**figure 3.10**) to understand how well they integrate into daily lives and routines and discover commonalities as well as gaps.

The implicit interaction framework does not have certain criteria to help locate where the works may lie. Hence, the mapping is subjective. In this thesis, a solution was considered to be more in the '*foreground*' the more consciously the user had to react to the system. For example, Baqai, et al. [11]'s virtual reality fruit picking completely takes the patient out of their environment and all their focus is on the game, while TumbleTooth [18] is integrated into a toothbrush and modifies the daily activity, putting it into the '*background*.' Virtual reality is more in the foreground than mixed reality, which is more in the foreground than a video game.

The initiative was rated through whether the system or the user reacts to the other and how one-sided this interaction is. A video game, for example, tells the user what to do and there is a clear right or wrong, making it highly '*proactive*.' The ReSwing [19], solely gives feedback on whether the user has done the exercise often enough, putting it at '*reactive*.' However, it is not the most '*reactive*' as it is also able to tell the user that the exercise has to be done again.

Three groups were identified through this mapping: proactive-foreground systems, reactive-foreground systems, and slightly-proactive-background systems.

The proactive-foreground systems consist of all technologies from **section 3.1** (gamified experiences) as well as one from the tangible technology section, which has a video game aspect to it as well. These tools prompt the user to do certain activities while also taking all of their attention. This is likely due to all these tools working similar to games, where users are completely immersed in just that activity.

The reactive-background group includes tools that are fully integrated into objects and activities the users were already engaging with daily. Here, the system does not need to signal the user to do anything, nor does it require any additional attention from the user.

The slightly-proactive-background systems are similar to the reactive-background group except that they are still the one to lead the interaction by encouraging the user to do their exercises. This encouragement, however, is not as invasive as the prompting that occurs in the proactive-foreground group.

It is noteworthy that most tools from **section 3.3** (integration into daily activities) can be found in the '*background*.' This suggests that the solution for knee injury patients should also fall in this area.

3.5 Chapter conclusion

This section looked at various different approaches aimed at improving physiotherapy adherence, specifically tele- and digital platform supplementation, gamified experiences, and integrating exercises into daily activities and objects. The integration of rehabilitation into daily activities shows significant promise in improving motivation while also minimising attentional demand.

Mapping the existing work onto the implicit interaction framework shows that solutions based on embedding exercise into daily routines demand less active attention, placing them in the 'background.' This area holds the greatest potential for the assignment and provides a foundation for the most effective design space.

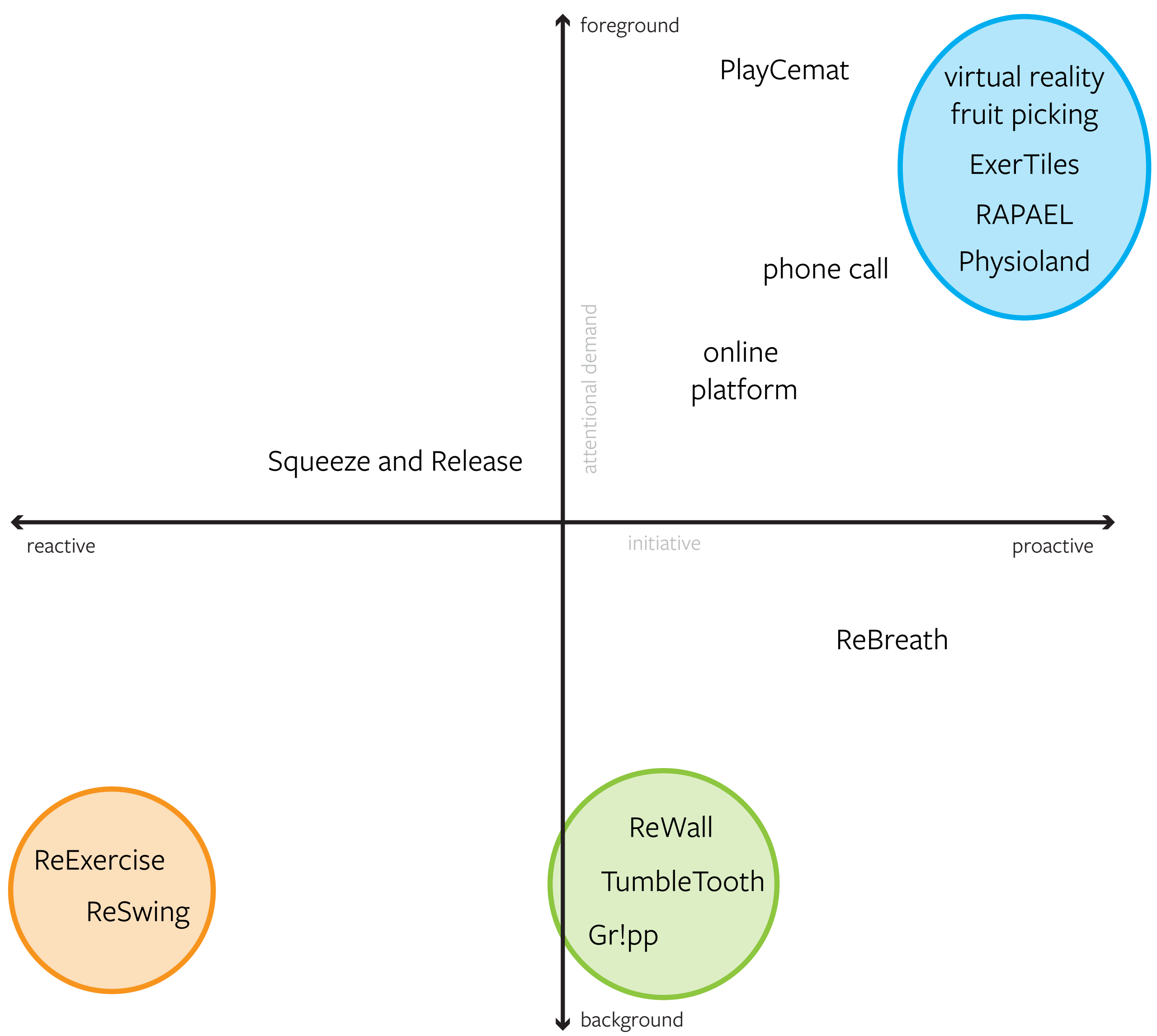


Figure 3.10 Related rehabilitation technology work mapped on the implicit interaction framework.

4 The daily routines of knee injury patients

While the literature covered in **section 2** gives an overview of knee injury treatments, it still lacks information about how patients integrate the suggested exercises into their daily routines. As this is required to be able to understand where an interactive technology can be implemented in daily objects and activities, interviews were done with knee injury patients. The interviews uncovered their daily routines, when they fit in their exercises, the level of motivation throughout the day, as well as their experiences with their injury and physiotherapy exercises.

4.1 Methodology

4.1.1 Recruitment

Participants were recruited through convenience sampling. They were required to either currently be under treatment of a physiotherapist or recently concluded their physiotherapy treatment. No injuries were excluded at this stage as the context research showed that the physiotherapy treatment for chronic and acute injuries are relatively similar (**section 2.1**). Three patients had chronic injuries while the other three had acute injuries. Sampling was done until data saturation was achieved.

A limiting factor of the convenience sampling is that all patients interviewed were students, which may not reflect the daily routines of a broader group of knee injuries. However, students are capable of having a mix of both active (sports, travelling between daily activities, etc.) and sedentary (studying, classes, etc.) lifestyles. Hence, these irregular and sporadic daily routines present to be a good target population.

Before the interviews were conducted, ethics approval was received from the Computer & Information Sciences committee at the University of Twente. All participants were briefed before the interview and asked to sign a consent form.

4.1.2 Set up

At the beginning of each interview, the participants were briefed on the activity: to create two timelines of their daily routines (one average weekday routine, one average weekend routine). They were given an example of a timeline to show what was wanted. This timeline included detailed events (**appendix A.1**), especially around the events when the knee was heavily used or not used at all. Further, the example also showed the thoughts surrounding motivation throughout the day.

In-person participants were given an A3 sheet of paper for each daily routine, as well as a wide variety of pens in different thicknesses and colours. Online participants were given a link to a Figma Jam and encouraged to use whatever tools they preferred (drawing tools, sticky notes, shapes, text boxes, etc.).

4.1.3 The procedure

The interview was done in an unstructured approach. The participants were told the goals and given instructions, but led the discussion. They were asked to think out loud and explain their day as they were creating their timeline. This unstructured set up allowed the participant to express their thoughts and experiences more freely, reflecting their true behaviours.

After the participant finished the timeline and were given the time to go back and change anything, a discussion was started about the events on the timeline, asking for clarification. Questions were prepared in advance to make sure certain topics were covered. All these questions were asked in relation to something the participant had written or said.

The interview was split into two sections; the weekday and weekend timelines. After the first timeline was completed and the discussion was had, the second timeline followed the same procedure. At the end, the participants were asked if they wanted to add anything else not yet discussed, which sometimes resulted in some interesting extra insights.

After the interviews, the timelines were scanned for safe keeping before notes were added and scanned again. These can be found in **appendix A.2**.

4.2 Findings

4.2.1 Exercise types

The patient interviews showed that there are two main categories of exercises they are required to do: strength and flexibility.

Strength exercises initially start as simple at home exercises using just body weight, increasing reps for increased difficulty. These exercises quickly move to utilising machines and heavier weights, meaning they are done at the gym with the proper equipment, which patients do not have at home. Examples of exercises that can be done without gym equipment include squats, hip thrusts, jumping squats, walking lunges, knee extension, airplanes, pistol squats, and knee ups.

Flexibility exercises focus on range of motion as well as helping against stiffness after prolonged inactivity. These exercises should be done by patients throughout the day to maintain the knee and limit pain. The most commonly mentioned exercises were heel slides, simply bending the knee or walking around, and table hangs. While these exercises are important, there is a bigger focus on strengthening since there are more muscles to target individually, which need to be used correctly for proper recovery.

4.2.2 Daily activities and pain

Certain actions may make the knee hurt more for some patients. A common theme was sitting. Most patients spent a prolonged amount of time sitting and working at a desk throughout the day, with only a brief break in the middle of the day for lunch. While working, they did not move their knee enough, and some were even inclined to raise the leg for most of this period of time. All these patients said that the pain came in a form of stiffness that would gradually go away as they started moving again, but that the initial movements were uncomfortable.

While the struggle for most patients was not moving enough, two patients had the issue that they moved too much, overstressing their knee. This happened when they either set themselves strict fitness goals or if they played a sport fanatically. In these cases, more caution and rest are needed.

4.2.3 Daily routines and exercises

Most patients did their knee exercises in the morning, whether this was an at home routine or a gym routine. This was mainly because motivation is still high at this point. If the exercises were postponed to the afternoon or evening, patients were more likely to keep postponing until simply waiting until the next day. It is, however, important to note that all participants were students, meaning they have more time and opportunity to exercise in the morning. Other patients might not have this time.

If patients already included exercise and sports in their daily routines before their injury, they were more motivated to do their knee exercises. Including knee exercises meant, for them, that they were still able to exercise when they would have otherwise played a particular sport. This could, however, also go the other way, and the exercises were seen as too boring and easy, putting them off the exercises. Other patients, who were not as exercise-motivated, saw their knee exercises as another task to add to their day, giving it a lower priority than hobbies and rest.

Further, patients noted that they were more likely to do at home exercises around a meeting with a physiotherapist. Before the meeting, they would do them to show their physiotherapist that they were doing the programme, while after there was more motivation due to the addition of exercises, which were seen as more exciting and fun to do.

4.3 Chapter conclusion: possible daily routine integration

As the project aimed to integrate exercises into daily routines, flexibility exercises were chosen as the direction to explore further. This is because strength exercises quickly progress to requiring gym equipment and are often done together with a physiotherapist on a weekly schedule basis than at home alone. The flexibility exercises are left to do by the patient themselves to maintain their range of motion.

The motivation to do at home exercises is highest during the morning, when a new day has just started. Patients will usually try to use this motivation, however if they wait, the motivation tends to decrease throughout the day. This either means the interactive technology needs to take advantage of the motivation in the morning or integrate with evening activities so that the patient does not require extra motivation.

Further, while many of the patients interviewed had an active lifestyle, they spend most of their day sitting, whether this is while they are working on a laptop, sitting in a lecture, or watching TV and playing video games. Most patients noted that their knee would go stiff if they sat in one position for too long and admitted that they should probably stand up and move more often. Hence, the target population hereafter focuses on people who sit while working for long periods of time throughout the day (e.g. a desk job or students).

5 Ideation

This section delves into the generation and evaluation of a range of potential solutions for the assignment. A requirement list was created to guide the ideation process. Next, a list of 100 ideas was generated from a broad range of perspectives. These ideas were then plotted on the implicit interaction framework and rated according to the requirement list to identify the most promising concepts. This then led to the selection of a final concept, which is developed further in the next phases of the project.

5.1 Requirements

To inform the ideation stage, the consulted literature, the interview with a professional physiotherapist, and the patients' daily routine interviews were reviewed again. The information was then condensed into a requirement list. With a requirements list, ideas can be generated and evaluated against a clear set of criteria, ensuring the prototype addresses identified needs.

The requirements were grouped into five different categories:

1. Assignment requirements
    - Requirements that were a given due to the nature of the assignment.
2. User interaction functionality requirements
    - How the idea/prototype should interact with the user and vice versa.
3. Knee functionality requirements
    - What the idea/prototype should specifically do in regards to the knee.
4. Safety
    - Features that make the idea/prototype safe to use.
5. Usability requirements
    - Requirements that affect how the idea/prototype can be used.

Each requirement was also given a 'weight' representing how important this requirement was. This weight was on a scale of 1 to 10, following the criteria in **table 5.1**.

Table 5.1 Scale used to assign weights to requirements.

	Importance	**Description**
10	Critical importance	Without it, the tool is fundamentally flawed.
9	Extremely high importance	Essential, absence would make the tool largely ineffective.
8	Very high importance	Absence would severely impact the functionality or usability.
7	High importance	Absence significantly takes away from the functionality or usability.
6	Significant importance	Absence may be noticeable and requires some effort to compensate for.
5	Important	Inclusion contributes to overall functionality or usability in a meaningful way.
4	Slight importance	Has value, but absence can be managed or worked around.
3	Minor importance	Has some value, but absence does not significantly impact the overall functionality or usability.
2	Very low importance	Absence is barely noticeable or easily compensated for.
1	Negligible importance	Inclusion has little to no impact on the overall functionality or usability of the tool.

For each requirement, the impact was analysed with the question *'what happens if this requirement is missing or poorly implemented?'* A difference was determined based on whether an absence would render the tool unusable, cause significant performance issues, would simply lead to minor inconveniences, or had no impact whatsoever.

A 10-point scale might seem large, but it provided space for subtle distinctions between requirements that may be close in importance but still not equal, especially towards the higher end of importance. For example, requirement 1.1 (**table 5.2**) is a critical requirement as it is a core part of the assignment. Without this, the tool would fail to meet the primary objective. Requirement 2.4 (**table 5.2**) was assigned a 9 as this was the approach to answer the assignment, but there might still be different approaches possible. Requirement 2.2 (**table 5.2**) received a score of 8 as feedback is important for the user experience, however the tool could still function without it. Similar reasoning was applied to all the other requirements.

The requirements list can be found in **table 5.2**. It is important to note that these are prototype requirements, and not requirements for a final product. A final product would include additional requirements for full-scale implementation, while the prototype requirements are designed to create a model that can test the core concept. Including requirements needed for a final product, which are not needed for testing the concept (such as the aesthetics of the product), might skew the points a concept receives.

Table 5.2 Requirements list for prototype.

Ref		Weight	Source
	Assignment requirements		
1.1	Must be integrated into daily routines and/or objects.	10	Assignment
	User interaction functionality requirements		
2.1	Must be able to track when the user is flexing/extending their knee as well as how much.	8	Interview with physiotherapist → would like to get numerical data to see how patients are doing. Interviews with patients → want to see how they are doing and whether they are improving.
2.2	Must provide feedback to the user about their knee mobility and whether they have moved enough.	8	Interview with physiotherapist → nice for patients to get feedback when they are home alone. Interviews with patients → would like to know when they are doing something wrong or right.
2.3	Could relay progress of knee mobility back to the physiotherapist.	3	Interview with physiotherapist → would like to be able to see how patients are doing at home
2.4	Must be intuitive to use in the sense that it should follow existing actions and not invent new ones.	9	Patient interviews → saw exercises as another task to do on a day, so would skip it
2.5	Could not depend on other devices (such as a phone or laptop) for basic functionality (not to run the prototype, but in the sense that it should not have it's basic functionalities on a different device)	2	Users might dislike needing to use the phone or computer after already spending most of their day using it [4].
2.6	Should have a quick daily set up (prepare and turn on) that does not take more than 5 minutes.	5	Patient interview → not add another long task to their daily routine.
2.7	Tracking and feedback should be able to be turned off easily while also not easy to accidentally trigger.	6	

2.8	Must not replace guidance from a medical professional. The tool should be used in parallel to physiotherapy.	10	Assignment → improve motivation and consistency. This is not a medical device.
2.9	Should not create a dependency where users feel they cannot manage without it.	10	Assignment → improve motivation and consistency. This is not a medical device.
2.10	Must encourage users to make safe and correct movements with the knee and not encourage unsafe and incorrect movements.	10	
2.11	Must not encourage users to push themselves further than they are able to.	10	
2.12	Must not be rigid or inflexible/restricting natural knee movements.	9	Assignment → integrating into daily routines should not hinder them.
2.13	Must not obstruct the user's range of motion or interfere with other daily activities.	10	Assignment → integrating into daily routines should not hinder them.
2.14	Should not be a foreground gamified experience.	7	Gamified experiences considered more fun, but there is an uncertainty about the long-term effect [11-15]. This thesis tries a different approach.
2.15	Must not just be a reminder or notification system.	10	Studies into reminder systems and adherence have conflicting results [5-8]. This thesis tries a different approach.
	Knee functionality requirements		
3.1	Must be inspired by knee injury physiotherapy exercises.	10	Assignment
3.2	Must encourage the user to keep their knee mobile throughout the day.	10	Patient interviews → after being inactive for a long period of time, the knee becomes stiff and starts to hurt.
3.3	Must not force the user to use the tool during a separate new event in a daily routine	9	Patient interview → not add another task to their daily routine.
3.4	The target usage period should be after range of motion has been restored and during the time that maintenance is a goal.	5	Patient interviews → beginning of recovery included a lot of resting and very careful movement In this phase of recovery, exercises are no longer as careful and incremental for flexing/extending. Maintenance is done by staying in motion [27, 30, 31].
3.5	Must not allow people to overextend or flex their knee too far based on the limits discussed with a medical professional.	10	The goal for flexion and extension can be a certain angle [27, 30, 31]. Users should not move their knee further than is considered safe.
	Safety		
4.1	Must be built to withstand regular use without breaking and causing injury.	9	If the assignment is to create something around daily objects/routines, it should be made to withstand this.
4.2	Must not cause skin irritation or pressure sores from daily use.	10	
4.3	Must not have sharp edges or points that could cause injury to the user.	10	
4.4	Any electrical components must not come in contact with skin unless required for the sensor.	9	
4.5	Materials that the user comes in contact with must be safe for the skin.	10	
4.6	Sensors should be waterproof.	4	
4.7	Any straps, fasteners, or adjustment mechanisms must be secure and not cause injury.	9	
	Usability requirements		
5.1	Should be adjustable to different sizes users may need, have a customisable fit, or be one-size-fits-all.	7	
5.2	Be portable to take to different locations, encouraging knee mobility throughout the day.	3	Patient interviews → moving location a lot throughout the day
5.3	Size should allow for easily handling and storage.	4	Requirement 5.2

5.4	Should not be easy to lose.	3	Requirement 5.3
5.5	Should not be overly bulky, making it difficult to transport.	4	Requirement 5.2
5.6	Should not have detachable parts that can be lost or damaged.	3	
5.7	Must be comfortable to use the entire period the tool is being actively used.	9	If the assignment is to create something around daily objects/routines, it should be made to be comfortable for constant usage.
5.8	Be usable for people with varying levels of mobility and recovery progress.	7	Flexibility is something that must be maintained throughout recovery, at different stages.
5.9	Should require minimal maintenance, reducing the need to repair components.	2	

5.2 Idea generation

5.2.1 100 ideas

The next step was to generate ideas. To stimulate a broad range of ideas, the approach was the generate 100 concepts without being limited by specific requirements. Quickly, it became clear that there were multiple recurring themes:

- Braces, bands, and monitors
- Clothing
- Shoes
- Furniture
- Other daily objects
- Toolkits
- Uncategorised

To reach the goal of 100 concepts, exceptional cases were also considered. These exceptional cases were concepts that are inspired by very specific cases, that would likely not integrate into a more general daily routine but do approach the problem from a different angle.

This unconstrained approach allowed for the generation of unexpected and potentially more diverse ideas. The subsequent section (**5.2.2**) explains how these concepts were evaluated against the requirement list.

The entire list of ideas can be found in **appendix B**.

5.2.2 Broadening the approach

During the idea generation, the approach was broadened. The initial method was to follow the approach of the research done in hand rehabilitation in stroke patients [16-18]. These papers integrated an interactive technology into objects of daily living. However, it became evident that in the context of knee injuries, this approach was difficult. When attempting to create a list of daily objects that are interacted with when using the knee, the list stayed short and surrounded clothing, shoes, and a few pieces of furniture such as chairs, making options limited.

Instead, the approach was broadened. Rather than just looking at daily objects, the entire daily routine can be taken into account. Focusing on routines opens up more moments through the day where patients naturally engage their knees, such as walking or standing up. An interactive technology can be introduced to these moments rather than relying on an object already in use. This follows Bagalkot, et al. [19]'s approach a little closer, where, for example, a mat was added to the porch swing to monitor exercise rather than directly modifying the porch swing.

This broadened approach still focuses on fitting into and being inspired by daily activities of knee injury patients while not being constrained to objects of daily living.

5.3 Evaluation of concepts

5.3.1 Implicit interaction framework

As was done with related work in **section 3.4**, all ideas were mapped to the implicit interaction framework to discover which ones to take forward. With the goal to integrate knee rehabilitation exercises into daily routines, the new concept would have to be more in the background. The initiative could be both on the proactive or reactive side – either the system guides the interaction (e.g. encouraging exercises), or a user already does something the system can recognise at react to (e.g. tracking exercises). This would mean that the optimal idea lies in the bottom two quadrants of the framework.

To see which ideas would fall within this area, all 100 ideas were plotted on the framework (**figure 5.1**). After plotting all the ideas, seven distinct groups appeared: tracking and feedback, tracking, movement assist, modified movement, movement cues, leg-controlled tools, and gamified prompts. The descriptions of each group are as following:

i. Tracking and feedback
   - Tracks the user's movement throughout the day,
   - Gives feedback based on the data collected from tracking the movement, incentivising the user to adapt their behaviour.

ii. Tracking
   - Only tracks the user's movement throughout the day,
   - The system does not do anything else with this data but can make it available for the user to access.

iii. Movement assist
- The tool helps the user move.
- For example, it may physically assist the user as they try to bend their knee.

iv. Modified movement
- The tool modifies the movements the user already does throughout the day.
- For example, a user might already walk in a certain way, but the tool will modify the way they walk to exercise their knee.

v. Movement cues
- The tool's objective is to get the user to do a certain movement.
- The tool prompts the user to do this movement until it is satisfied that the user has done the exercise properly.
- It usually requires the user to do the movement multiple times throughout the day.

vi. Leg-controlled tools
- A daily object that is modified so it requires the user to use their leg to use it.
- This changes the way the user interacts with the object so that they use their knee in a certain way.

vii. Gamified prompts
- A tool that approaches exercise from a heavily gamified perspective.
- The movement is encouraged through a game-like interface.

The three groups that are closest to the preferred criteria are tracking, movement assist, and modified movement. Unfortunately, the tracking group misses vital requirements by only tracking movement and not doing anything with this data. Movement assist and modified movement both work by influencing movements that the user already does throughout their day, which matches the earlier criteria.

5.3.2 Requirements list

The 100 ideas were also compared to the requirement list in **section 5.1.** Certain requirements and sections were not yet considered at this stage since the concepts are just ideas and not yet physical prototypes. This includes all of the safety requirements as the concepts do not yet consider how they may be prototyped. Additionally, requirements 2.3, 2.6, 2.7, 2.10, 2.11, 3.5, and 5.9 were not considered yet. This is because these requirements are either about how the prototype is made, or would require testing to discover what it is capable of doing and can be more easily tweaked afterwards. The top 5 ideas can be found in **table 5.3**.

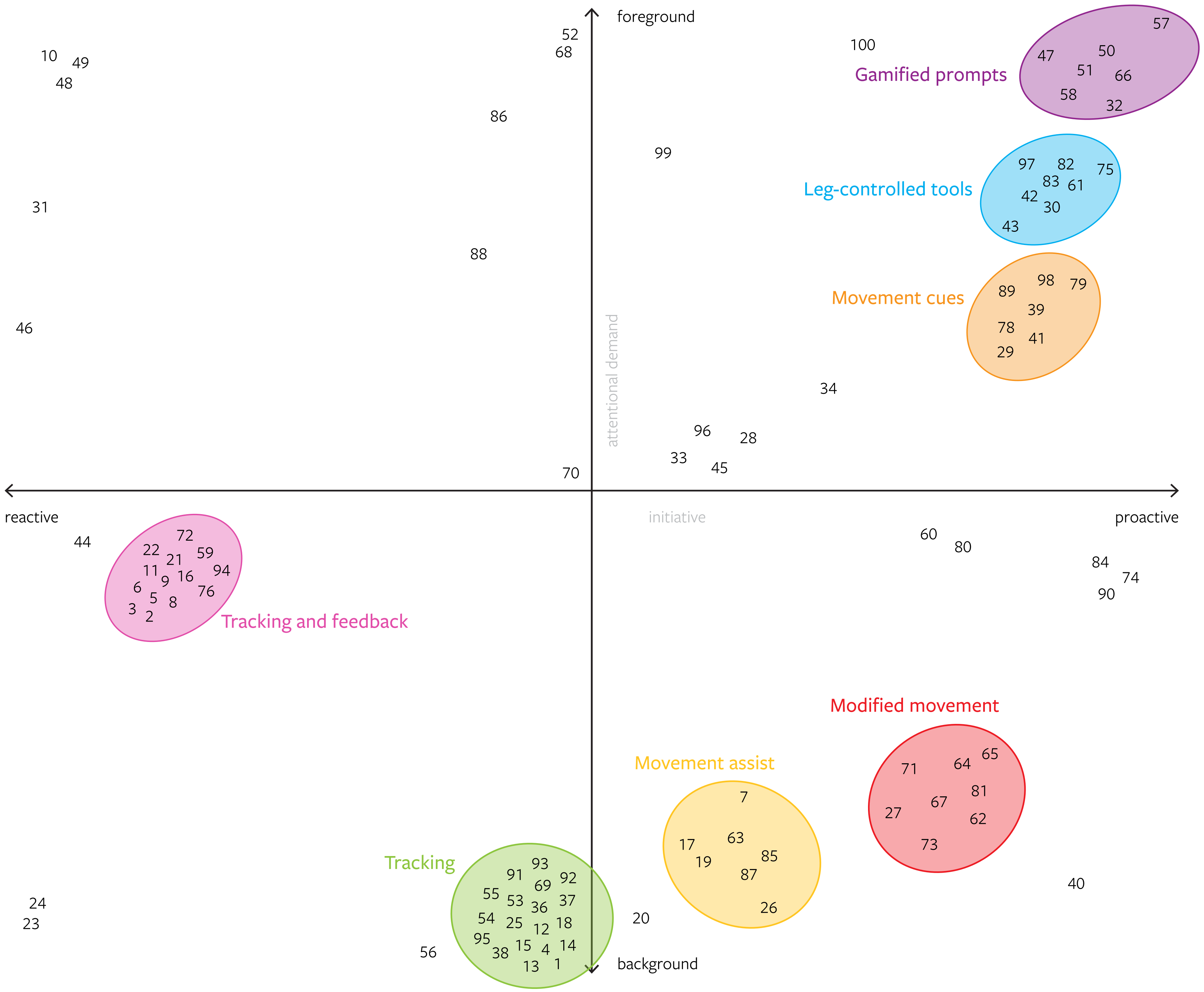


Figure 5.1 All 100 ideas mapped onto the implicit interaction framework.

Table 5.3 Top 5 ideas based on requirements list.

	Idea	Points
1	29 – Move around edge of shoe on floor to move around knee. Shoe gives a reminder, user does it, shoe tracks movement throughout day.	166
2	96 – Furniture slider. A 'slider' that can be attached to different types of furniture (table legs, chairs, bookshelves, etc.) allowing somebody to extend and flex their knee while around this furniture.	159
3	97 – Mat overlay. An overlay to put on existing mats and shows how a user should move their leg to encourage knee movement.	155
3	98 – A pedal that can be transported and used in different contexts: at a desk, at the dining table, while sitting on the couch.	155
4	90 – Gardener: a gardening stool that helps user bend their knees in a safe way rather than kneeling all day.	150
4	89 – Photographer: adjustable tripod that changes height based on knee movements.	150
4	32 – Shoes that project a path onto the floor that the user must follow, practicing different step sizes for different levels of extension/flexion. Only does this when people haven't moved enough yet.	150
5	75 – Construction worker: a ladder that uses leg controls to move and change height.	149
5	27 – Shoes designed with a sole that requires a slight knee bend to engage, for knee flexion and extension during walking.	149

To view all ideas versus requirements list, refer to **appendix C**.

5.3.3 Implicit interaction framework and requirements list

Comparing both the results from the implicit interaction framework and the requirements list, it quickly becomes apparent that they do not align. Almost all the ideas in the top five from the requirement list can be found back in the upper two quadrants on the implicit interaction framework, while the desired location would have been in the lower two. This could mean that not enough weight was given to requirement 2.14 as **section 3.4** showed gamified experiences were in the upper quadrants. However, it does not feel appropriate to give this requirement more importance as it does not fundamentally impact the usability. Instead, a new approach or perspective was needed.

In response, two new ideas were generated: a maze and a roller. These ideas were generated based on the requirement list as well as the desired location on the implicit interaction framework. The main goal behind both was to find a way to assists users with their exercise that does not simply remind them to move.

A maze would require people to follow a certain path with their foot as they sat to extend and flex their knee in the process, while a roller would allow somebody to extend and flex their knee themselves. Both these ideas can fall into the background since a user can do these activities while focusing on something else, meaning they fall in the lower two quadrants of the implicit interaction framework.

Comparing the ideas to the requirements list, the roller gets 166 points, and the maze gets 159 points, which puts them at place 1 and 2 respectively in the top 5 ideas list in **section 5.3.2**. This would mean that the roller would be the best idea to move forward with. However, there are some further considerations to take into account.

The roller scores high because it is able to track how somebody uses it, can give feedback, can be used by people in different phases of recovery, and can be easily transported to be used in multiple locations. Further, rollers are already commonly used in the physiotherapy domain, showing that they are effective for treating injuries. However, when attempting to develop this idea further, it quickly became apparent that there was not much to innovate in this area. A self-rolling roller can become dangerous, and a roller with a reminder system does not assist with an exercise any more than a normal roller would.

On the other hand, the maze concept can assist the exercise. This idea mainly lost points by not being as portable as the roller. However, this can also be remedied by having a look into which materials might be appropriate. The maze can be inspired by the same exercises as the roller as well as make it more 'fun.' Further, there are ways it can be personalised for each user. Hence, the maze idea was taken further.

5.4 Chapter conclusion

The ideation phase explored a wide range of possible solutions, starting with the creation of a requirements list and the generation of 100 ideas. During the generation of these ideas, the approach was broadened, shifting from solely thinking of daily objects to considering all daily activities to investigate more areas of potential interaction.

This long list of ideas was systematically narrowed down using the requirements list and the implicit interaction framework. However, these two methods generated different conclusions as all concepts considered 'best' through the requirement list did not land in the desired quadrant of the implicit interaction framework. Two new ideas were generated based on these findings.

The 'maze' idea ultimately stood out as the most feasible solution. Despite not being as portable as the 'roller', the maze offers greater potential for enhancing engagement and supporting exercise routines in a more enjoyable and customisable way. This section sets the foundation for the next steps in development, where the maze concept is refined and later tested.

6 Concept Development

Building upon the maze concept in the previous section, the next phase focused on developing the concept through multiple iterations. The following section delves into the prototyping process, involving three iterations of varying fidelities (one low fidelity and two medium fidelity prototypes) to refine and evaluate the concept.

6.1 Low fidelity prototype

6.1.1 Shift from maze to mat

While the maze concept was chosen to be taken forward, it still presented with limitations. The first issue, as mentioned in the previous section, was the portability of the tool. A maze requires parts that allow a user to move one way but not in other ways. The initial concept saw this as a groove cut into a board, which would be too large and heavy to carry around. A thinner more flexible material would be able to be folded up, but would eliminate the static maze.

Further, a static maze lacks customisability, which affects both accessibility and motivation. Accessibility is impacted by the inability of the exercise to be adaptable for different phases of recovery. A user who has only recently injured themselves might not yet have the same range of motion as a user multiple weeks in their recovery. This inability to change the maze may also discourage users to consistently use it as the exercise will become repetitive and boring. A more customisable tool would mitigate this.

Combining the solutions to these two issues introduces a shift towards a mat. A mat addresses the portability issues as it can be folded up and so more easily transported. Additionally, it provides the user the option to move in all directions, encouraging movements that cater to their progress and length.

Hence, hereafter, the concept will be referring to a 'mat' and a 'slider' instead of a maze.

6.1.2 Description of the concept

The concept (**figure 6.1**) consists of a mat placed underneath a desk, which extends in front of the chair to user is sitting on, and a slider where the injured knee's foot is positioned to make sliding movements smoother. The mat would use sensors to detect inactivity and would incorporate a notification system to prompt the user to move. At this stage in the prototyping, how this would work

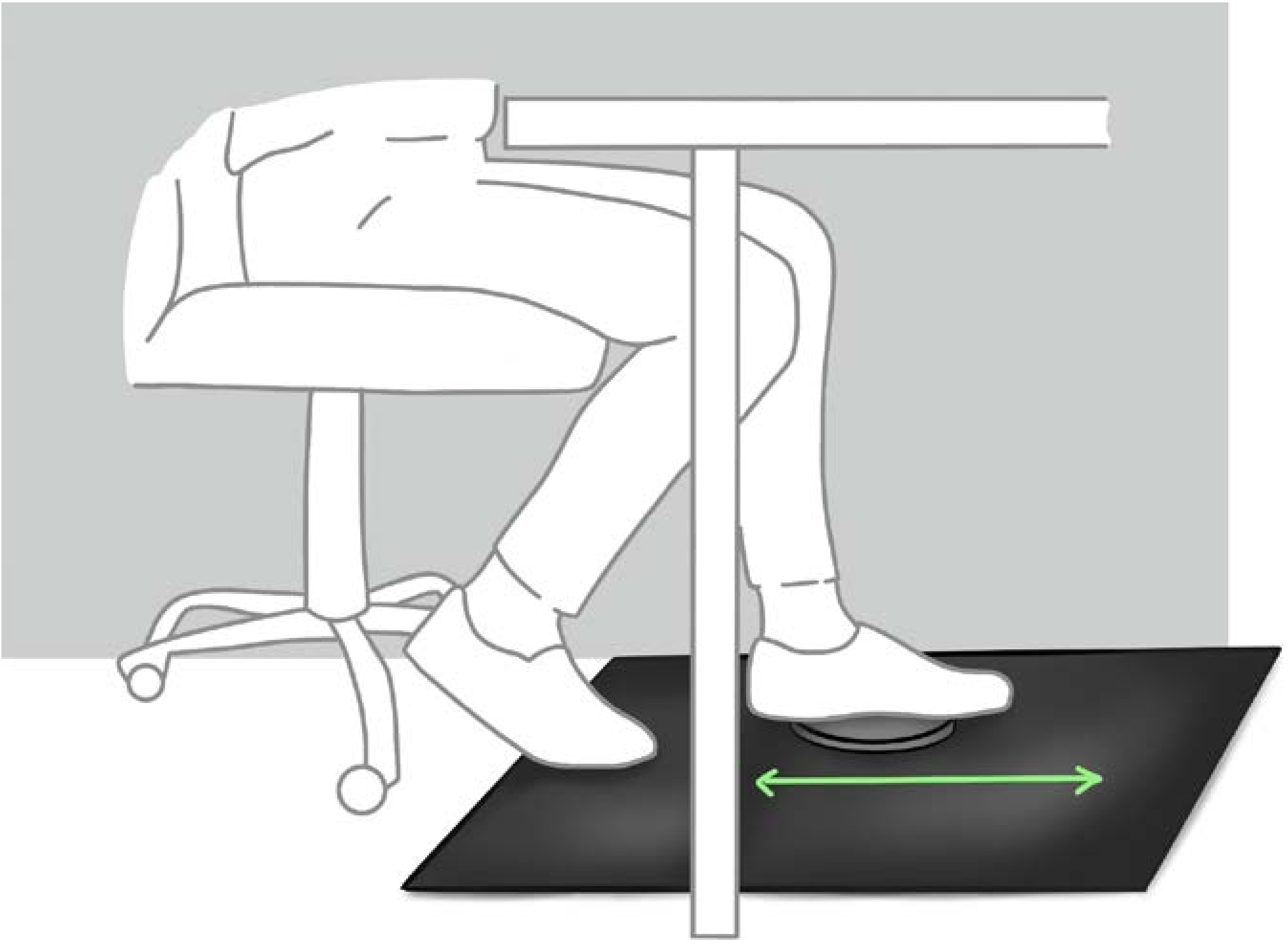


Figure 6.1 Initial mat and slider concept

was not yet considered. This low-fidelity prototype was simply used as a proof of concept and made out of a plastic lid as slider and plastic bag at mat.

The mat would have the ability to monitor the user's activity as they sit and would be able to detect periods of inactivity. After a predefined period of inactivity, the user is prompted to move their leg to flex and extend their knee. The mat would then guide the user as to how they should move their foot: forward, backward, left, right, or on a diagonal through either visual, auditory, or tactile alerts. There could be an option to base these instructions on the user's activity patterns throughout the day to provide a more personalised exercise routine. When the user performs the required movements, the mat would detect this and ends the exercise session, resetting the inactivity timer.

Components:

- Mat: Placed underneath the desk, extending in front of the chair.
- Slider: A movable platform where the injured knee's foot is placed, allowing for easy sliding movements.

Features:

- Inactivity detection: the mat can measure the user's activity.
- Prompting: after a predefined period of inactivity, the user is prompted to move their leg.
- Exercise guidance: the mat guides the user to make movements (forward, backward, left, right, diagonal), which can be based on activity throughout the day.

Use:

1. The mat is places underneath a desk, extending in front of a chair.
2. The foot of the injured knee is placed onto the slider.
3. After a predefined period of inactivity, the user is prompted to move the knee (extend/flex) by sliding their foot over the mat.
4. The mat and slider guide the user how to move their knee.
5. Once the exercise is completed, the user returns to their resting position and the inactivity clock restarts.

The features and technical specifications of this concept are explored over the different prototyping stages discussed in the next sections.

6.2 Medium fidelity prototype iteration 1

While creating the first prototype, a number of factors were taken into consideration: the size of the mat, the directions for the exercise, and the user interaction with the mat.

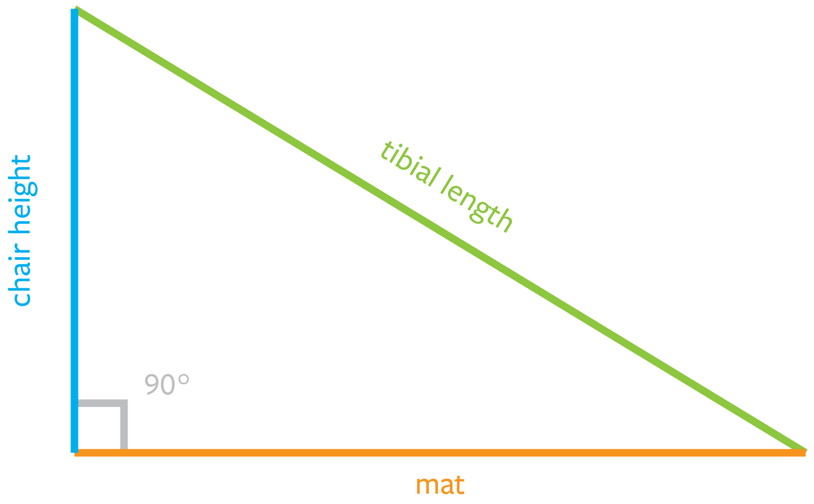
6.2.1 Size of the mat

To calculate a rough estimate for the size of the mat, the Pythagorean theorem was used including average tibial length, average foot length, and average seat height. Aitken [39] discovered that the mean tibial length is 39 cm, with a range of 30.8–46.5 cm. Shoe store *Sacha* found that the average shoe size for men in the Netherlands was around 43 [40] (equal to around 27 cm foot length). For this purpose, knowing only the average shoe size for men was enough as men tend to have larger sizes, and the mat also needs to accommodate this size. The average seat height was taken from the European Ergonomics standard NEN-EN 1335, which mandates that chairs must have a seat height of 40–51cm [41], averaged out to 45 cm.

Tibial length and foot length were added together to account for how far the toes would reach when at 0° extension (as seen in **figure 6.2**). Using the Pythagorean theorem, a minimal length for the mat was calculated to be around 45 cm.

Since average tibial length does not account for the length of the patella or the foot height, the taller range of the tibial length was also used to calculate a length. Further, this upper range was also calculated since Dutch people tend to be taller than the world average. This came out to be around 56 cm.

As the mat should be bigger than the range of the movements done during the exercise, the mat was made 60 cm in length, which could later be changed if evaluations showed the length did not work.



average tibial length = 39.0 cm (from range of 30.8–46.5 cm)

add the foot length = 25 cm

= 64 cm

average chair height = 45 cm (from range of 40–51 cm)

mat = $\sqrt{(\text{tibial length}^2 - \text{chair height}^2)}$ (from Pythagorean Theorem)

average size = $\sqrt{(64^2 - 45^2)}$ = 45 cm

longest size = $\sqrt{(71.5^2 - 45^2)}$ = 55.56 cm

Figure 6.2 Calculating the length of the mat using tibial length, foot length and seat height.

6.2.2 Exercise inspiration

Inspiration for the movements the mat should encourage was taken directly from range of motion exercises given to patients for their knee. Specifically, these exercises were towel slides and wall slides. During a towel slide, the patient sits on the floor, puts their foot on a towel and slides their foot back and forth to maximum extension and flexion. A wall slide is very similar to this, but the patient has to slide their foot up against a wall. This led to the vertical track for users to follow during the exercise.

To make the exercise less repetitive in one direction, inspiration was also taken from the hip abduction exercise, where a patient is expected to move their leg away from the midline of their body either laying down or standing up. This exercise is mainly a strength exercise and not a range of motion exercise. However, when in combination with the vertical movements, it might make users move their knee in ways they otherwise would not do during their exercises but would during daily use. This led to the horizontal track that can be found on the mat (**figure 6.3.1–3**).

6.2.3 Description and user interaction

The first interaction the user has with the mat is folding it out onto the floor in front of the chair they are sitting on. They turn on the mat and place the injured knee's foot on the slider. While the mat is idle, it emits a blue light (**figure 6.3.1**). After a certain period of inactivity, the mat will turn yellow (**figure 6.3.2**) to warn the user to start extending and flexing their knee, following the tracks as drawn out on the mat with the LED lights. If they have not yet done this when the lights have turned yellow, the lights will turn red (**figure 6.3.3**). The mat stays this colour as the user does the exercise and returns back to blue when the user has completed the exercise. In the case of this prototype, all feedback is visual. The lights are used as a reminder system, a reaction to the user's behaviour, and as a guide for the exercise.

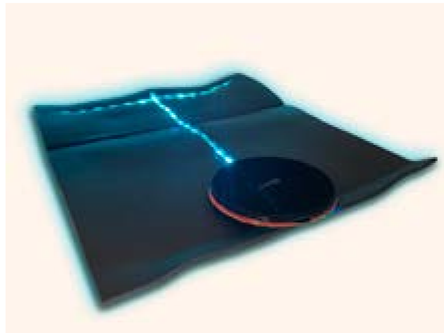


Figure 6.3.1 Idle state of mat

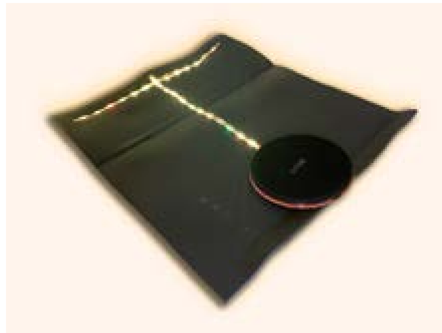


Figure 6.3.2 First warning to start moving.

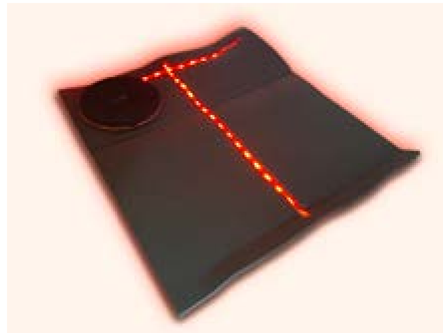


Figure 6.3.3 Final warning to start moving.

6.2.4 Evaluation

The evaluation of this prototype was done by running through the way the users would interact with the mat to see if there were any short comings. The first thing noted was that having the mat folded up made it relatively cumbersome to transport. This was not possible with the current prototype as the electronics were stuck to a cardboard board. Finding a material that could roll up would easily remedy this.

The material also had to be revised to make the sliding motions easier. The top layer of the mat was made out of a yoga mat, however, even in combination with a slider used for core exercises, this material did not allow for smooth sliding motions. Another thin layer would have to be put on top to make the exercises easier to do.

Further, it was noted that the way the colours of the lights were utilised was not the most user friendly. Keeping the light red while doing the exercise might come over as doing something wrong, and the yellow as first warning was not urgent enough with the brightness of the LED lights. Hence, this was something to revise.

In addition to the colours needing revision, putting the prototype in the situation where it would be used showed that the lights may not always be visible. Hence, another feedback method would be needed to give the warnings. This could,

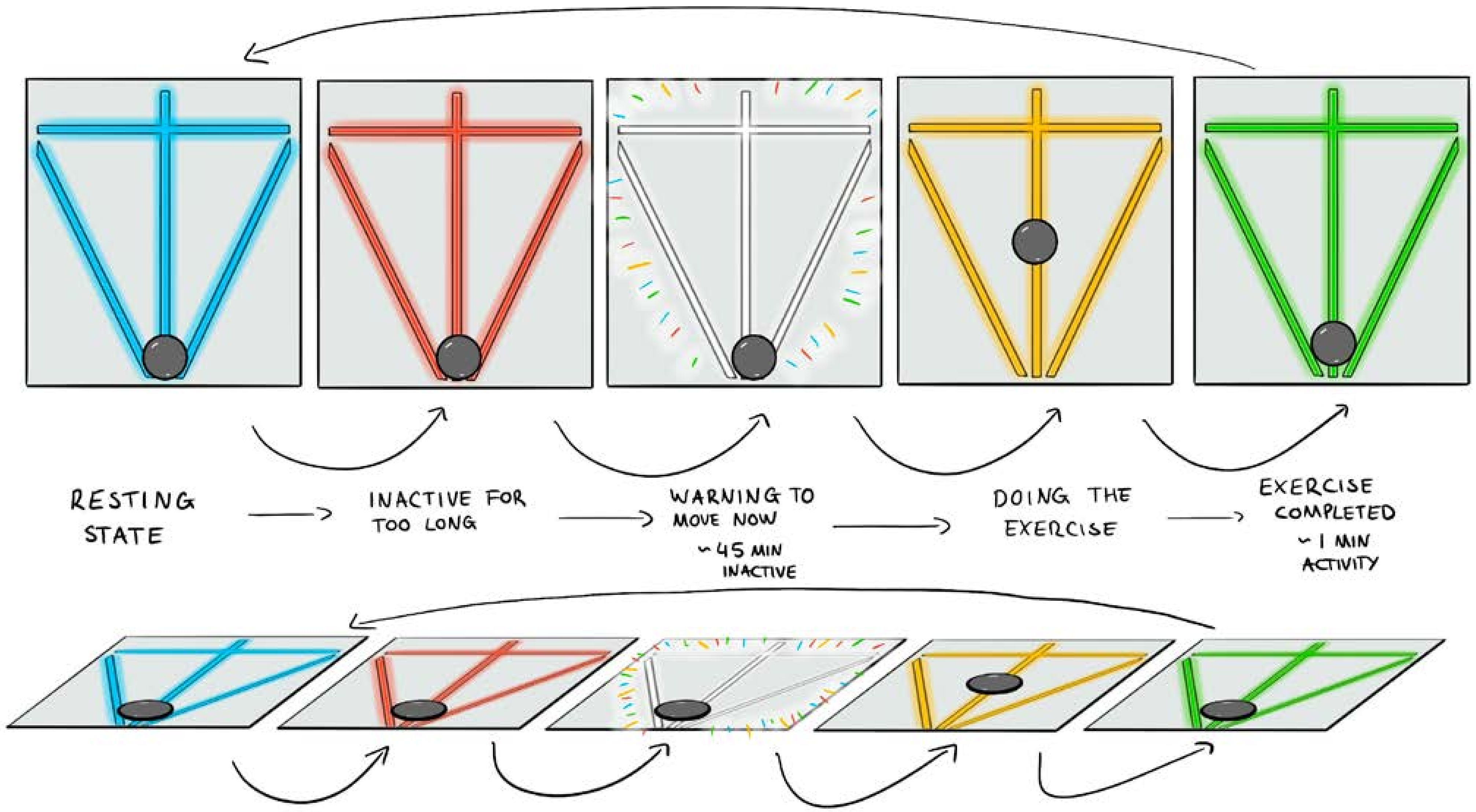


Figure 6.4 Instructions given by the mat in form of coloured lights

for example, come in form of vibrations in the slider or an extra light on a table. These points were taken into consideration when creating the second prototype.

6.3 Medium fidelity prototype iteration 2

The second prototype aimed to find solutions for the points brought up in the evaluation of the first prototype, to then get feedback from physiotherapists to discover if experts believe the solution may help knee injury patients.

6.3.1 Modifications

The general concept in this prototype is still the same as in prototype 1. Hence, only the changes made will be discussed. For a overview of the concept, refer back to **6.1.2** and **6.2**.

To make the exercise more dynamic and free moving, a connection was made between the two directions of the exercise, adding a diagonal track in addition to the horizontal and vertical tracks inspired by towel/wall slides and hip abductions. While this diagonal is not directly inspired by knee injury physiotherapy exercises, it does follow a natural movement that people may make in their daily lives.

The colours of the lights were also reconsidered to match the instructions better (**figure 6.4**). During the idle state, the mat emits a soft blue light. Then, when the user starts to reach the point where they should be moving again, the mat will turn red as a warning. When the maximum limit of inactivity has been reached, the mat will flash with different colours to get the attention of the user. When the user does the exercise, the mat is yellow, and when they finish, the mat turns green as a confirmation. Finally, the mat turns back to blue.

To mitigate the issue that the user might not see the lights when the mat is underneath a desk, an extra display was proposed. This display can be placed on the table where the user is working and mirrors the colour of the lights on the mat.

Further, the mat was also made out of a new material. By using two layers of yoga mat, the prototype was now able to be rolled up, making it much easier to transport. The top layer also had less of an antislip coating, making the sliding easier. However, the sliding motions still were not as smooth as desired. Hence, the slider was also given an elastic so it could be held onto the foot tightly.

6.3.2 Physiotherapist evaluation

The evaluation of this prototype was done in collaboration with a physiotherapist. They were shown the prototype (**figure 6.5**) along with an explanation of how the user would interact with it. The overall impression was good and they were able to give some pointers to help with the next prototype:

- Instead of the mat only extending in front of the chair, it could go underneath the chair as well. This would allow the user to practice flexion as well rather than be limited to 0° to 90°, especially since most patients have difficulty with flexion and tend to rest at full extension.
- The ideal exercise would have the user flexing and extending their knee from 0° to 130°.
- The vertical and diagonal sliding motions were seen as most useful for patients at all levels of recovery.
- The horizontal motion was not as appropriate for the initial stages of recovery and targets the hip more than the knee. But it is something that can be used for patients further on in their recovery.
- When asked how often somebody should move when sitting at a desk working, they noted that it depends on the patient, but that every half hour is a good place to start.
- When asked about how the mat can also show progress, they suggested that the lights could show how far the user was able to extend and flex their leg.

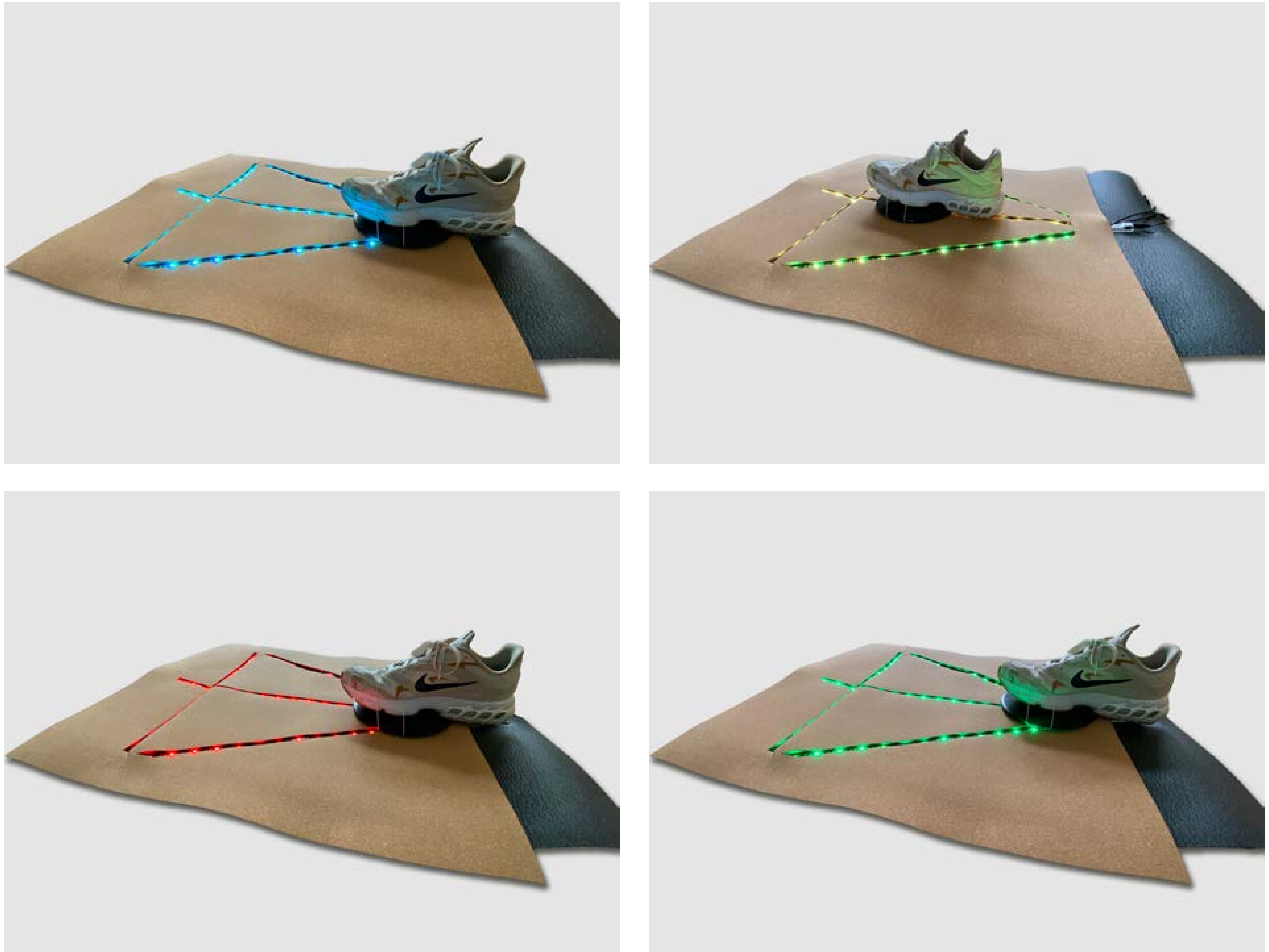


Figure 6.5 Prototype 2 blue resting state, red warning to start, yellow state while doing exercise, green completion feedback.

7 Final Prototype

The final prototype (**figure 7.1**) was created as the working prototype to test and evaluate. Before this prototype was created, a few more changes were made to the concept based on the feedback in **section 6.3.2**. Finally, all features were made functional up to the point that the prototype could be tested. This chapter explains what changes were made to the concept, the technical specifications of the prototype, and the limitations of the prototype.

7.1 Concept changes

Some slight changes were made based on the feedback and other realisations from the previous prototype. First, the mat was made longer so it can be placed underneath the chair as well to accommodate for the 90°–130° flexion. Second, the horizontal sliding exercise was removed. Third, the 'resting state' of the mat now had the LEDs turned off so it does not draw too much attention in between exercises. And fourth, instead of an extra display to put on the table so users can see when the mat is alerting, a vibration clip on the shoe prompts users to move and notifies them when they have completed the exercise. This full concept can be seen in **figure 7.2**.

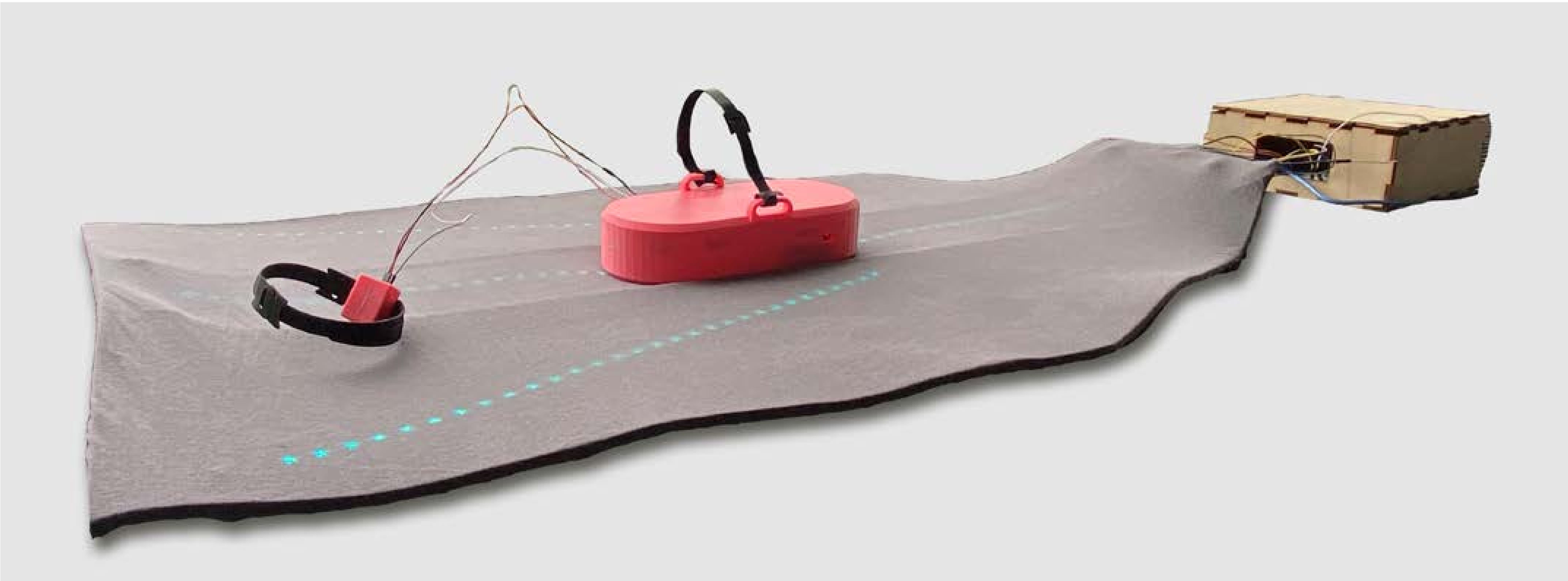


Figure 7.1 Slide view of final prototype. A mat with a slider and vibration anklet.

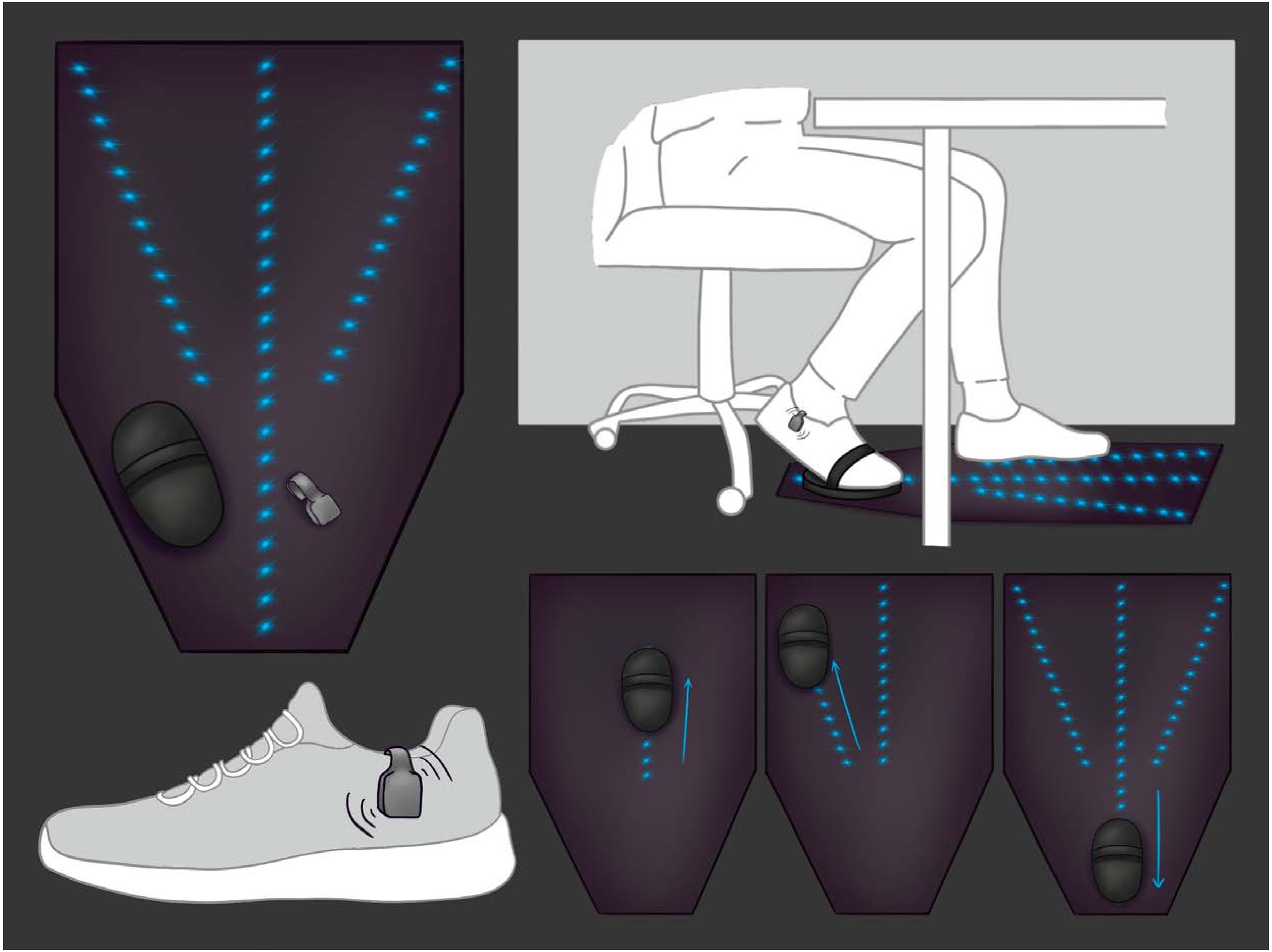


Figure 7.2 Mat, slider, and vibration clip concept for final prototype.

However, since the main goal of this prototype was to test, it was not created exactly according to the concept. A couple of compromises were made:

i. The original concept allowed the user to move freely on the mat with the slider and the mat would recognise this. However, this would require creating an intricate grid to recognise the position of the slider. Hence, for testing purposes, only the back-and-forth movement is registered at intervals of 6 LEDs, which would ideally be every LED.

ii. Based on i, the mat has 'rails' integrated into it so that the user stays within the movement range that the mat and slider can register.

iii. Rather than creating a clip that would fit on different models of shoes, testing the feasibility of the concept and feedback methods was more important. An anklet with a vibration module was created instead.

iv. A button was added to the slider to set off the starting command so the testing was not reliant on set timing in case more time was needed between trials.

7.2 Technical specifications

The prototype consists of three parts: a mat, a slider, and a vibration anklet (**figure 7.3**). The mat controls LED lights, the slider recognises where the user currently is on the mat, and the vibration anklet gives the user vibrational alerts.

Hardware	
WS2812b LED light strip	Individually addressable RGB LED lights in a strip. There are 60 LEDs per meter, and it runs on 5v. It can be cut into smaller sections.
Solderless LED strip connector x 2	Makes it possible to control cut off sections of the LED strip without needing to solder the wires.
Arduino UNO x 2	Microcontroller that's easily programmable. One needed for slider, one needed for the mat to control separate parts without the need for long wires.
RFID RC522	RFID/NFC reader/writer compatible with the Arduino UNO.
NTAG215 NFC stickers	NFC stickers with a memory of 504 bytes and can be read from 5 centimetres away. Memory is not important for this prototype, but distance is so the reader does not read the wrong tag. Hence, a simple NFC sticker was chosen.
Ai-Thinker NRF24L01+ Wireless Module x 2	A wireless communication module that allows Arduinos to wirelessly communicate. One can be a receiver while the other is a transmitter.
Vibration DC Motor Module - 3.7-5.3V	A small flat vibration motor module that can easily be connected to an Arduino. Used to create the vibration in

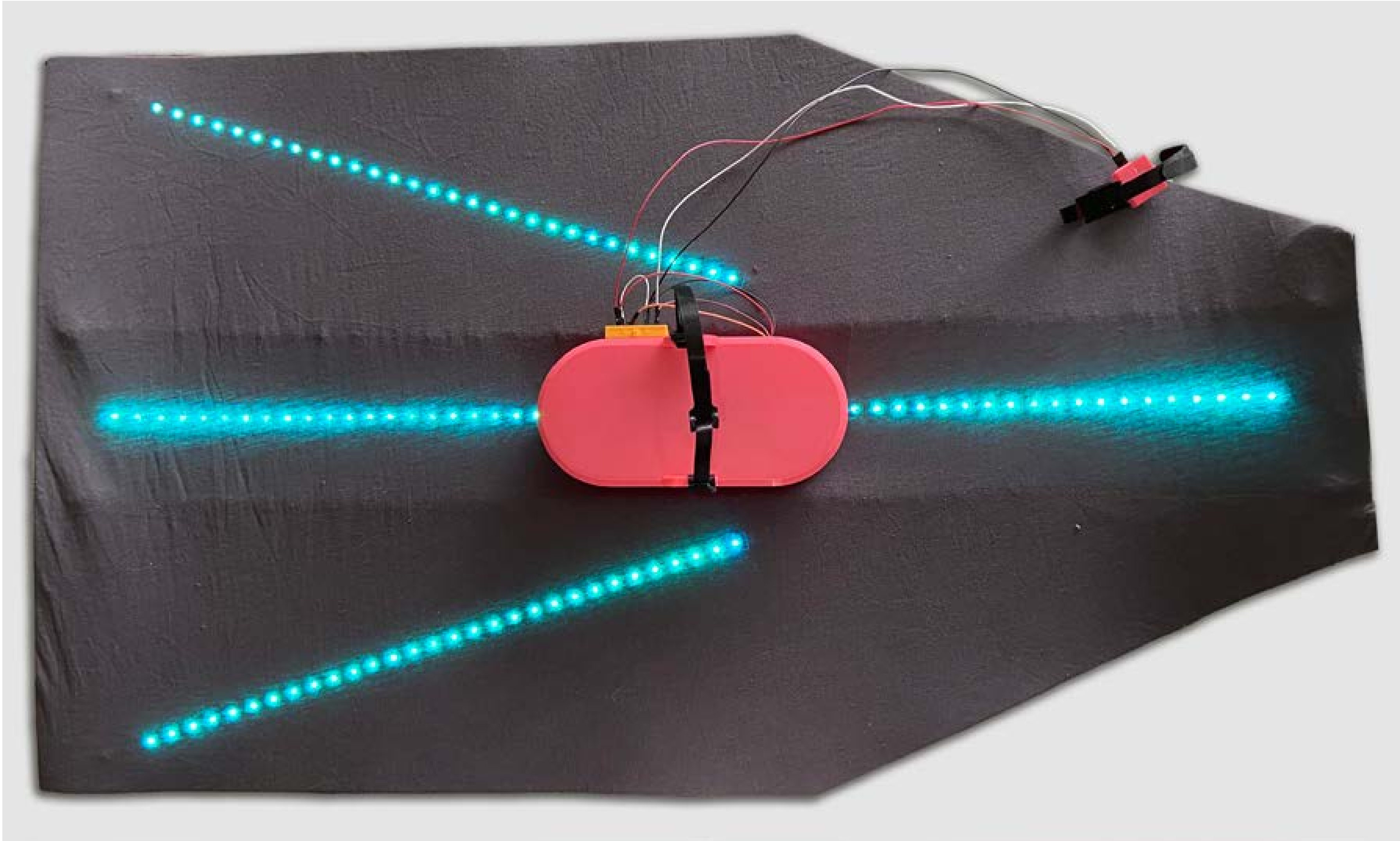


Figure 7.3 Top view of prototype with mat, slider, and vibration anklet.

More specific descriptions of how these components work together can be found in **sections 7.3** and **7.4**.

7.3 Mat

The base of the mat is made of a yoga mat. This makes sure that the mat will not slip while being used and is also easy to roll up for transportation. Three LED strips are stuck on this mat. Only the middle strip is accompanied by NFC stickers, which are stuck next to the LEDs they will turn on. Further, 'rails' are made from fabric so the slider will stay on track while being tested. Using fabric for this means the mat can still be rolled up. All three LED strips are controlled by separate pins on an Arduino uno. A wireless module allows the Arduino uno to receive information about which lights to turn on from the slider in **7.4**. Finally, everything is covered by a thin cotton fabric to make the sliding movement smoother and to cover the inner workings. The hardware on the mat can be viewed in **figure 7.4**.

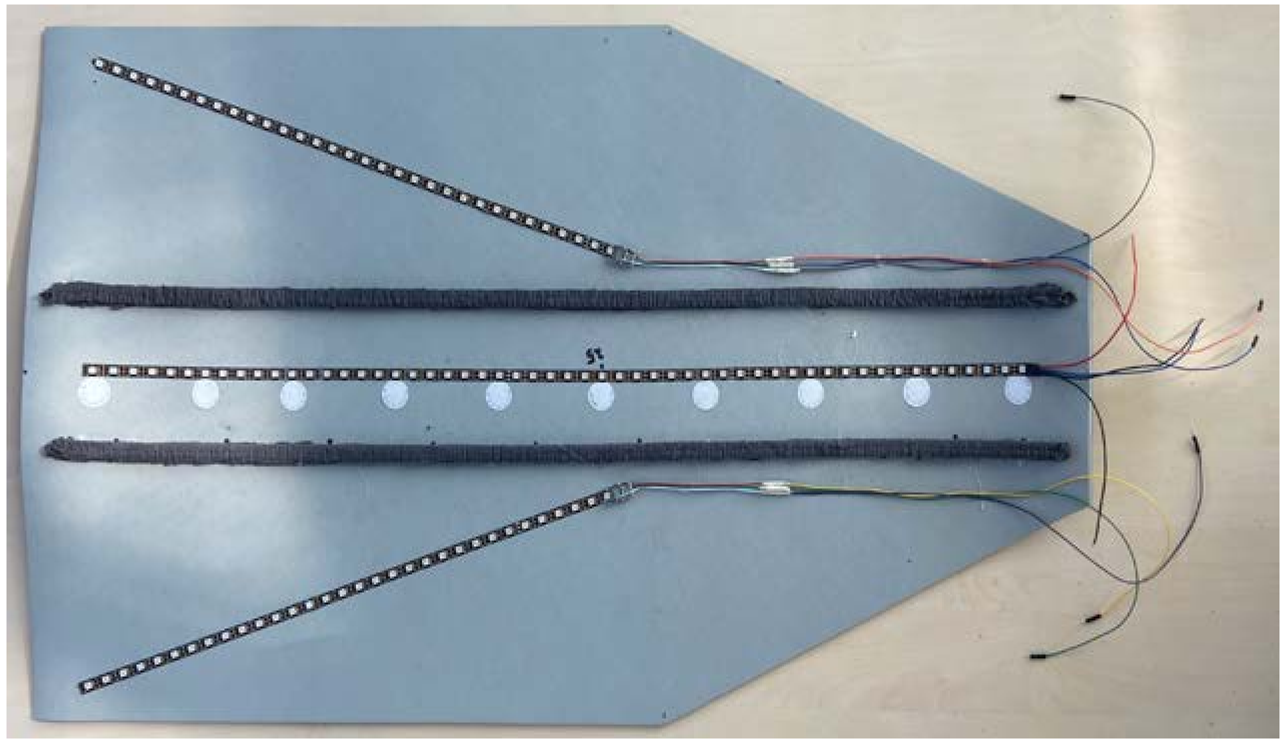


Figure 7.4 Hardware on the mat.

7.4 Slider and vibration anklet

For programming purposes, the slider and vibration anklet (figure 7.5) are connected to the same Arduino uno. This means that the anklet is still physically connected, while it would be optimal to have this communicate wirelessly as well. The slider has an RFID reader to read the NFC stickers on the mat in 6.4.3. Finally, a wireless module allows the Arduino uno to transmit which LEDs to turn on to the mat's Arduino uno.

A button has been added to the slider purely for testing purposes. While the concept has the mat reminding the user to move every 30 minutes, this would require a very long testing session with users. Instead, the button sets off the reminder sequence in the vibration anklet and sends the command to the mat to flash.

Unfortunately, the slider had to be made thicker than desired to accommodate for all the hardware. This was considered okay for testing, but would need to be made much thinner in practice.

7.5 Limitations of the prototype

As mentioned in the previous sections, the prototype is not without limitations. As is, it is not able to test free movement on the mat, nor do the two outer LED strips work as intended. They copy the commands given to the centre LED strip to simulate the intended function.

Further, the slider is much too bulky and not the optimal shape or size. However, fitting the hardware was prioritised over the ergonomics in this case. This also affects the vibration clip, which is now less convenient to use in the form of an anklet.

However, this prototype was still able to test the important aspects of the concept: how it is used, whether the feedback is considered relevant, whether users would consider using this in their daily life, and whether it is too distracting from the daily activities it will be integrated with.

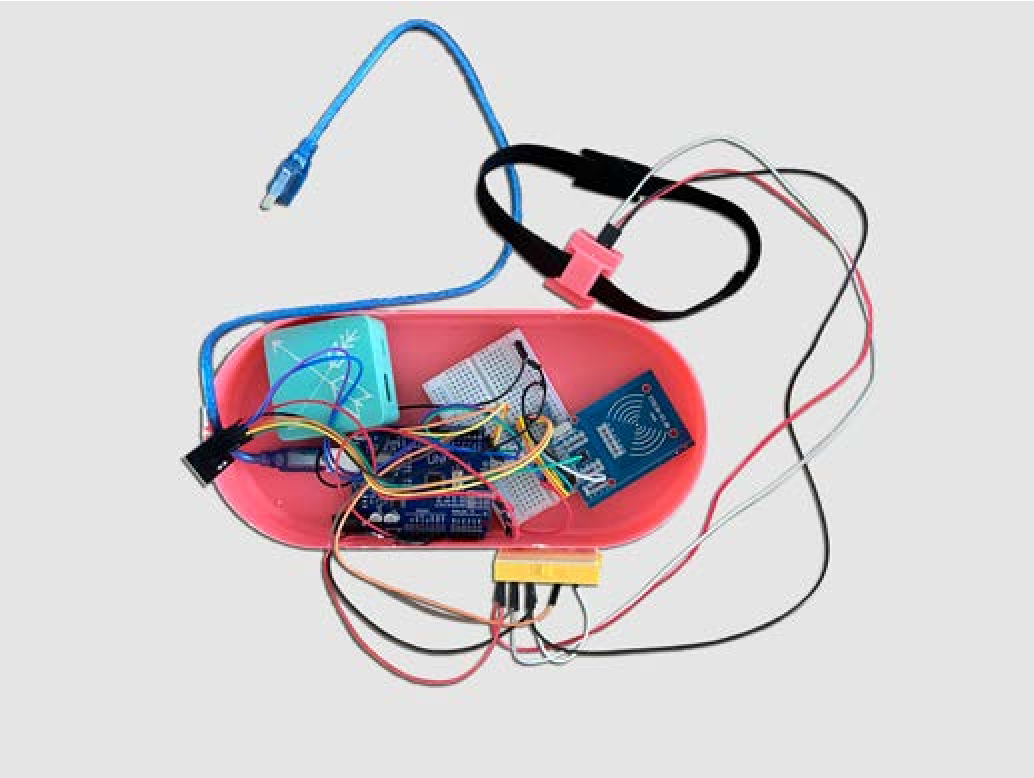


Figure 7.5 Hardware in slider.

8 User Evaluation

The original research question aims to investigate how an interaction technology can be designed to improve at-home physiotherapy adherence. However, due to the nature of the master thesis, a long-term study like this was not feasible. Hence, a different evaluation was required.

'Adherence' was looked at from a different perspective. Looking back at the requirements list in **section 5.1**, the user tests mainly aimed to see if the 'user interaction functionality,' 'knee functionality,' and the 'usability' requirements were fulfilled. A particular emphasis was put on requirements 2.1, 2.2, 2.12, 2.13, 3.1, 3.4, and 5.7. Most of these requirements may affect adherence as they influence the ease of use as well as the relevancy for the patient. The table below showcases these requirements and how they were tested:

Table 8.1 Requirements and how they were tested during the user evaluation.

Ref	Requirement	How it was tested
2.1	Must be able to track when the user is flexing/extending their knee as well as how much.	Observation as the participant is using the prototype.
2.2	Must provide feedback to the user about their knee mobility and whether they have moved enough.	Feedback from participants to discover if they understand it and whether they believe it is relevant.
2.12	Must not be rigid or inflexible/restricting natural knee movements.	Observation as the participant is using the prototype as well as feedback from the participant.
2.13	Must not obstruct the user's range of motion or interfere with other daily activities.	Observation as the participant is using the prototype as well as feedback from the participant. A dual-task experiment to see if using the prototype interferes with the ability to do a task that requires thinking (explained in s**ection 8.1.4**).
3.1	Must be inspired by knee injury physiotherapy exercises.	Ask participants whether they were prescribed similar exercises.

3.4	The target usage period should be after range of motion has been restored and during the time that maintenance is a goal.	Feedback from participants that asks if they would currently use it and/or when in their treatment they would have used it.
5.7	Must be comfortable to use the entire period the tool is being actively used.	Feedback from participants.

8.1 Methodology

8.1.1 Ethics approval

Ethics approval was received from the Computer & Information Sciences committee at the University of Twente, and all participants signed a consent form before the evaluation sessions began.

8.1.2 Participant recruitment

Participants were found through convenience and snowball sampling. Because of this 7 out of 10 participants were students, and the 3 other participants were working at the time of testing. Jobs included were in the area of IT and academics. This covers the target that tends to sit at a desk for long periods of time throughout the day to work population (as determined in **section 4.3**).

No limitations were put on the injury the participants had except for the injury not being too recent to prevent accidentally exacerbating the injury. Four participants had acute injuries including ACL tears (treated with and without surgery), cartilage injuries, and a meniscus tear. The other six participants had chronic injuries including patellofemoral pain syndrome, hypermobility, tendon infections, and overuse injuries they were not able to name but had been officially diagnosed by a medical professional.

8.1.3 Set up

While the prototype would ideally be usable in any location the user prefers, all tests were done in a controlled environment to test the use case of working at a desk. The set up was made to copy this environment as closely as possible.

Participants were asked to come to a pregiven location. This location was a quiet room on the university campus. Here, they were asked to take seat on the chair already in position with the mat and at the desk. After helping them place the foot of their bad knee on the slider, as well as putting on the anklet, they were then told to move the chair until they sat comfortably. This would hopefully replicate a situation where they work at a desk themselves.

The researcher sat on the other side of the table, careful not to interfere with the mat, so the participant was able to look at them as they spoke and did not have to strain their neck.

The set up can be seen in **figure 8.1**.

Figure 8.1 Set up of user evaluation sessions.

8.1.4 Procedure

The sessions began with an explanation of the concept (as in chapter 7) and that this prototype was not a completed product. After asking the patient what their injury was and whether they were given a sliding exercise as part of their recovery therapy, participants were asked if they had any questions before the sessions were explained (which was also given to them in writing with the consent form). Once again, participants were free to inquire questions.

Following these preliminary explanations, the session proceeded with a test run to familiarise the participant with the 'dual task' they would perform during the evaluation to measure the 'cognitive load' of the task. Cognitive load theory, first introduced by Sweller [42] in 1988, suggests that individuals can only process a limited amount of information at any given time, and overloading this can hinder task performance. The test conducted measured how the dual-task scenario impacted task performance, drawing on the methods of previous research by Serrien [43], Van Impe, et al. [44], and Leone, et al. [45], by assessing the number of mistakes made and the time taken to countdown from a given value in steps of three. The duration of this part of the session varied between 10 and 17 minutes depending on participant speed.

The test run was done in two steps. First, the participant was asked to count down in steps of three from a given number. Thereafter, the participant was asked to do the same but while also making use of the prototype – sliding their foot forward and backward. This allowed the participant to get used to both the cognitive and motor task they were asked to do, preventing confusion during measured trials.

Before the measured trials began, a video recording was started. This video recording captured audio as well and put the prototype and foot of the participant in frame. Then, five measured trials were done. First, the participant would only count down without using the prototype, next they would count down while simultaneously using the prototype. This meant they were asked to count down 10 times, each iteration starting with a different value. The values were all in the same range to prevent some values taking longer to speak out loud than others.

The second part of the evaluation sessions included two questionnaires. The first questionnaire was the NASA task load index, and the second was a questionnaire created specifically for the prototype (**appendix D**). The NASA task load index is a list of 6 questions with 21 degradations aimed at assessing workload for a task. The second questionnaire comprised of 8 questions with 7-point Likert scales.

Finally, the session ended with a semi-structured discussion. There were three questions each participant was asked about what daily contexts they can see it being used, the frustrations with using it, as well as improvements they'd like to see. They were given the chance to note anything else they thought was important as well. The researcher then checked over the answers to the questionnaires and asked any addition questions for clarification. This discussion was also captured in the audio of the video recording (which was still pointed at the prototype).

8.1.5 Pilot session

The test went through a pilot session and the starting values given to the participants were edited as well as the frequency of the dual tasks. The feedback questions went through another pilot session, whereafter a more elaborate discussion moment was added.

8.2 Data measuring and analysis

8.2.1 Dual-tasks

The video taken of the dual task experiment was analysed and cut into 10 parts (5 single tasks, 5 dual tasks). Markers were added in iMovie to each point where a participant finished saying a number out loud. The average time taken per value for each trial was calculated by measuring the time taken for the entire arithmetic task (end of starting value given to end of last value said by the participant), and then divided by the number of values the participant gave (number of markers).

The number of mistakes was counted by checking whether a value was correct based on the previous value said out loud. This meant that making a calculation error somewhere did not automatically mean the following values were incorrect. For example, if a participant went from 155 to 151, this would be counted as a mistake. But if the next value was 148, this would not be counted as incorrect. It would be incorrect to say 149, even though this would be the expected value if the mistake had not been made.

Whenever a participant corrected themselves after saying a value, the last value was counted, not the first. For example, if a participant first said 125 and then corrected it to 124, the end of the second value was marked and the first value was disregarded. If the second value spoken out loud was correct, the earlier mess up was not considered a mistake. If the second value was incorrect, however, even if the first value was correct, it counted as a mistake.

The average time taken for each value and percentage of mistakes made was then compared based on whether it was a singular task or a dual task for each participant using a two-way ANOVA.

Finally, average dual-task cost, measuring the cost of doing the dual-task compared to the arithmetic task [44], was calculated by normalising the values for average increase in time taken and average increase in mistakes made between -1 and 1, where a negative value means the participant did better during the dual task, adding these values together, and then dividing them by 2.

8.2.2 Questionnaires and discussion with participant

An average of the answers to each question in the questionnaires was calculated. Even though there were only 10 participants, so not much can be taken away from the statistical data, the answers give an overview of what they thought of the prototype and the workload.

The points mentioned in the discussion were compiled into list and are discussed in **section 8.3.1**.

8.3 Results

8.3.1 Feedback received from participants

8.3.1.1 Intention to use

Participants had a range of different knee injuries ranging from unidentifiable chronic pain to ACL tears. There seemed to be a clear distinction between participants with chronic injuries and those with acute injuries in terms of whether or not they would use the prototype in daily life. 5 out of 6 **participants with chronic injuries** indicated that they **would not use** it as the sliding movement was often not included in their exercise program and could sometimes even aggravate their injury.

However, 3 out of 4 **participants with acute injuries saw value** in the prototype, especially in later stages of their recovery. This acknowledges that that recovery processes are highly individualised, with one participant even mentioning being explicitly told not to perform sliding movements during their recovery (other participants with the same injury were told to do such exercises).

The feedback indicated that **participants who were already motivated to exercise** or move more often throughout the day were **less likely** to see a need for using the prototype in daily life. On the other hand, participants who found themselves leading a more **sedentary lifestyle** were **more excited** about the prospect of using the prototype every day. The participants who did see themselves using the prototype appreciated that the prototype could easily be rolled up and transported to different locations.

8.3.1.2 Feedback system

The feedback (vibration and LED lights) was generally understood and thought of as helpful by 9 out of 10 participants. However, participants **valued the vibration more** than the lights as the lights were usually not visible underneath the table. Others considered the lights distracting because they had an urge to look down at them. Conversely, other participants liked the addition of visual feedback as it visually confirmed that their movement had been recognised.

The **intention behind the LED feedback** was not always understood by the participants. They expected the lights to behave differently and give feedback on other aspects of the exercise. For example, two participants expected that the lights would show them a goal for how far to extend their knee, or one participant expected it to follow the back-and-forth movement and not just how far they extended or flexed their knee. This shows a mismatch between what the user expects and what the mat shows them.

Three participants also noted that they would like to **have a counter** that shows how many reps they had done or still had to do. This would mean there would be one less thing for them to think about as they were already doing the two tasks in the dual-task experiment.

8.3.1.3 Comfort of use

Design-wise, the only thing noted by the participants was the ergonomics of the slider. 5 participants explicitly mentioned that the **slider tested was too thick**, causing some discomfort when sitting. Further, it also made participants very aware of it, which is not needed when their knee is something they are already thinking of during the day. This, however, was already expected as the dimensions were based on the hardware rather than ergonomics.

While the participants only put on and took off the slider once during the session, some also mentioned that it might be too much of a hassle to do that every time they want to use it. This could possibly make it less motivating to do the exercise every half hour.

8.3.1.4 Perception of the dual task

Finally, most participants noted at some point during the user testing that they **felt like they were slower and struggling** more with the arithmetic task during the dual-task trials than the singular task trials. Although the data shows that, on average, the difference was a fraction of a second (**section 8.3.3**), the feeling of struggling is also important. Users may be less likely to use the device if they feel it hinders their work.

A full overview of the participant's feedback categorised in benefits and barriers can be found in **figure 8.2**.

8.3.2 Use of the prototype

While the participants were using the prototype, some small design issues were observed. First, most participants did not use the length of the entire mat, but rather a small section. For some, this was because they had shorter legs than the range provided, but other others this was because they did not extend and flex their leg as far as possible. This suggests that the prototype does not encourage full extension/flexion.

Another issue was an issue in the design of the Arduino program. When the participants moved their foot back as far as possible, the lights did not go on as far as they reached. This was because the RFID reader was at the front of the slider, while the NFC stickers were positioned based on the back of the slider. Because of this, the full range of motion was not displayed. However, this likely did not change the outcome of the evaluation sessions and can easily be fixed in the code.

Further, half of the participants were not aware that the LED lights were showing how far they had reached during the exercise. This is likely because the table was in the way, and they could not see the lights turn on as they did the exercise. It could be possible to display the information after the green completion flashing lights, or the information must be communicated in a different way.

benefits

- can be taken to different locations
- easier than standing up and moving
- less distracting from work that standing up
- relevant for short-term use with acute injuries

barriers

- exercise not as revelant for chronic injuries
- slider too thick/uncomfortable to use
- when very focused, can miss the vibrational feedback
- LEDs not visible and distracting when want to view
- LEDs do not show/behave as expected
- no way to see the number of reps
- have to strap in every time

Figure 8.2 Overview of benefits and barriers based on participant feedback.

8.3.3 Cognitive load

As the sample size (10) of the user testing is small, the outcomes cannot be generalised, however they were still looked at to see if there is a potential for future research.

Appendix E shows the relevant statistical results. The mean time per value for the dual task was 2.01 seconds, while the mean time per value for the single task was 1.85 seconds. The mean for each participant can be found in **appendix E.2**.

A two-way ANOVA (**appendix E.1**) with p-value 0.05 showed that there was no significant interaction between the type of trial (dual or single task) and participant ($F = 1.668$, $p = 0.110$), suggesting that the effect of the trial type does not vary significantly across participants.

At $F= 5.427$, $p = 0.022$, the trial type is statically significant at the 5% level, meaning that the type of trial has a significant effect on the average time per value. In other words, **the time it took the participants to calculate and say the next value out loud depends on whether the trial was a dual-task or single task.**

The final **average dual-task cost** of all participants came out to 0.085. With a maximum of 1 and minimum of -1 possible, this **affect seems miniscule**. Average cost of all individual participants can be found in **appendix E.3**.

8.4 Discussion

8.4.1 Results discussion

The results highlight several important aspects of the prototype's performance in relation to the requirements investigated (**table 8.1**). While the prototype demonstrates that it can track knee movement and provide feedback, there is a mismatch between the LED feedback system and what the participants expect from it. Some participants expected more detailed guidance from the lights, and some believed it to be irrelevant all together. Additionally, the slider's thickness currently can impact long-term user engagement as the comfort of use is not yet optimal.

The dual-task results, although the sample size was small, also revealed interesting insights, particularly a difference between perceived and actual cognitive load. Although the statistical data showed significant yet minimal impact on task performance, participants noted that they felt like they were struggling more when using the prototype while doing the arithmetic task. This perception of increased effort, despite the in-actuality minor time difference, suggests that the prototype might be perceived as disruptive, challenging the idea that it can be integrated into daily life.

However, overall, the insights indicate that the prototype shows promise with further refinements, especially in the areas of feedback and ergonomics.

8.4.2 Limitations

The user testing was not without limitations. The sessions did not put the prototype in an actual use-case scenario, where the participant does their own work and the prototype alerts them ever 30 minutes to move. A more long-term study could show different insights into the usability of the prototype and whether participants believe it integrates well into their daily life or not.

Further, the prototype tested did not allow for free movement and guided the participants to easily move their leg in a straight line. The concept initially intended for users to be able to freely move over the mat. It is possible that less guidance with the sliding movement would have affected the task differently.

Additionally, the mat going off every half hour could possibly come unexpectantly for the user. To save time and have more control over the experiment, a button was pressed to start the starting signal 20–30 seconds later. This interval was random to create a sense of unexpectedness, but the participants were waiting, so it never came as a surprise.

By asking the participants to say the values out loud and measuring the time between when one value was said and the other, there may be errors in the data. Different numbers have different syllables, making some longer to say than others. To mitigate this, starting values were all within the same range, but it could not be completely prevented.

The starting values all being in the same range also came with other issues. Certain values would repeat, and the arithmetic task became easier as time went by. The issue could also be blamed on the fact that the increment to decrease with was always kept the same so participants would not get confused with the repeated trails. Patterns were recognised, making it less of an arithmetic task and so changing the workload.

Another factor than may have influenced data is how some patients began to recall numbers in the rhythm of the movement they were doing with their leg. This begs the question whether they knew the answer before and were just following this rhythm, or if this somehow synced up anyway. Two participants also explicitly noted that they noticed they started doing this.

This dual-task experiment only tested the effect using the prototype had on an arithmetic task. However, most people do other work throughout the day. Repeating the test with different tasks might bring up other significant effects. Additionally, this test did not investigate how the exercise is affected by the dual task, which could also be an interesting perspective to investigate.

Finally, a significant limitation of this study was the number of participants (10). Their feedback was valuable, but (although the cognitive load results were deemed significant) it is hard to draw conclusions from such a small sample. More participants could be included in addition to different tasks as aforementioned.

8.5 Conclusion

While the user evaluation provides valuable insights into the usability and cognitive load of the prototype design to aid at-home physiotherapy adherence, several limitations prevent definitive conclusions. The small sample size and artificial nature of the setup restrict a full comprehensive understanding.

Nevertheless, the dual-task experiment showed that the prototype did significantly affect participant's cognitive load, through the increase in time per task was minor in the big picture and average cost was miniscule. However, participants also realised themselves that they needed more focus to complete the dual task than the single task. This may hinder the proper integration of the exercise into the daily activity.

Feedback from users suggested that the prototype has potential, particularly for those with acute knee injuries. But the feedback system needs refinement, particularly the LED lights. It might be possible to communicate information and provide feedback without the need to use visual feedback.

A long-term study in real-world environments with a more diverse participant pool and varied tasks might improve the understanding of the prototype's impact on adherence as well as the user experience attached to it.

The results from the user evaluation were then taken to physiotherapists for them to provide feedback on the prototype as well. This is discussed in the following section.

9 Physiotherapist feedback

After the user evaluation, the prototype was shown to four physiotherapists. One of these physiotherapists was the same physiotherapist who gave feedback in **section 6.3.2**. The goal of these interviews was to collect feedback from a professional perspective regarding these requirements:

Table 9.1 Requirements investigated with physiotherapist feedback

Ref	Requirement
2.1	Must be able to track when the user is flexing/extending their knee as well as how much.
2.10	Must encourage users to make safe and correct movements with the knee and not encourage unsafe and incorrect movements.
2.12	Must not be rigid or inflexible/restricting natural knee movements.
3.1	Must be inspired by knee injury physiotherapy exercises.
5.7	Must be comfortable to use the entire period the tool is being actively used.

9.1 Methodology

The prototype was set up in a room at the physiotherapist office, where the physiotherapists were told what the concept was as well as that the prototype had its limitations. They were shown a short demo and were given the opportunity to test out the prototype themselves as well.

Afterwards, a short discussion was held. Each physiotherapist was asked whether they believed the exercise would be beneficial, if they would consider giving it to patients, which patients they believed it would benefit the most, whether they saw any potential risk (based on the one participant in the user evaluation who mentioned not being allowed to do that exercise), if they had any pointers to make it more effective, and if they had any other feedback to give.

Notes were taken during and after the interviews.

9.2 Results

9.2.1 Appropriateness of exercise

Overall, the physiotherapists were happy with the concept and believed the prototype could be given to patients to take home. All four especially saw potential for acute knee injury patients in the beginning phases of their recovery. Since the current prototype was said to mainly be good for blood flow, one physiotherapist suggested adding weight to the slider for chronic injuries with treatment plans that require more strength training.

As in **section 6.3.2**, the same physiotherapist commented that the diagonal movement was less relevant. This is because it is already a less natural movement for most people, so could be more uncomfortable for knee injury patients. The other three physiotherapists did not say this explicitly, but did say that the back-and-forth motion was most like the one they would prescribe to their patients. The idea of freedom of movement instead of a forced straight forward and backward movement was not rejected, as this allows patients to move their leg as they deem comfortable.

Further, when asked about whether this exercise comes with any risk, directly related to the participant in the user evaluation who had been told to absolutely never do that movement, all four physiotherapists did not believe there would be any issues. However, they did also mention that all treatment plans are on a case-to-case basis and there can always be individual reasons why certain exercises are discouraged.

9.2.2 Feedback on design

Two physiotherapists noted a design issue with the slider. Since the entire foot is on the slider, it is not possible to achieve full extension of flexion when sitting down on a chair since the ankle gets in the way. For full extension the patient needs to shift to their ankle at some point, and for full flexion, the patient needs to shift to their toes. To show the issue, they demonstrated this as well with the prototype's slider.

Finally, one physiotherapist suggested adding a 'competition element' to the concept to encourage the patient to push further and want to achieve a better extension and flexion. They imagined this might enhance adherence by making the exercise more gamified.

9.3 Discussion

9.3.1 Results discussion

The feedback from the physiotherapists generally supports the potential of the prototype, particularly for acute knee injury patients in early recovery stages, which reinforces the conclusions from the user evaluation (chapter 8). This suggests that the target group could be narrowed down to cover only acute injuries and not chronic injuries. However, there was also a suggestion to make it more relevant for chronic injuries by adding the possibility to add weight to the slider. This would have to be investigated further to see if it is an appropriate solution for this group.

In terms of the design, the issue with the slider restricting full knee flexion and extension is a clear challenge. While this was not explicitly brought up by the participants in the user study, this was something noted by two physiotherapists. This suggests that, for optimal use, the slider would have to be redesigned to allow for a better range of motion.

Finally, there was also a suggestion to gamify the concept. However, looking back at the user evaluations, no participant requested this when asked what would make them more likely to use it. This might be because the participants did not want another thing to think about while doing dual tasks. However, it might be a more valuable addition if the concept is used during a more idle daily activity, such as watching TV.

9.3.2 Limitations

While the physiotherapist feedback sessions provided valuable insights into the prototype's potential use, several limitations of the study should be considered. First, the physiotherapists only tested the prototype themselves and did not use it in collaboration with any knee injury patients. Without observing how patients interact with the prototype, valuable feedback on usability and unforeseen challenges may have been missed.

Second, the physiotherapists' perspectives are shaped by the specific patients they typically treat and their preferred rehabilitation methods. This is also why their feedback has been incorporated, as they are professionals. However, there are also physiotherapists with different experiences, as shown with the one participant in the user evaluations that was not allowed to do this specific movement. A broader group of physiotherapists might lead to more variety in feedback.

Finally, given that the feedback was based on a brief session and demonstration, the physiotherapists might not have been able to fully imagine how long-term use of the prototype could affect patients. This might have missed some concerns with long-term use.

9.3 Conclusion

The concept was considered to be a good idea by the physiotherapists. They agreed that in its current state it is most relevant for acute knee injury patients in the beginning stages of their recovery. However, some small tweaks would increase the potential further. These improvements mainly focus on the slider, where a modification is required to give the user more range in their movement and weight can be added to increase the challenge.

10 Discussion

The research question of this thesis was as following:

How can an interactive technology object of daily living be designed to improve at-home physiotherapy adherence for knee injuries?

This chapter aims to answer this question by discussing what arose in the previous chapters.

10.1 Literature and patient interviews

To uncover the possibilities for the interactive technology, the process began with a literature review and interviews with knee injury patients. This showed that there are two types of knee injuries: acute and chronic. Treatment plans depend on the type of injury, as well as how severe it is. The patient interviews quickly showed that almost all patients deal with stiff knees when they find themselves sitting for long periods of time. Hence, this was the direction taken for the design of an interactive technology over strength training.

Research into physiotherapy adherence highlighted multiple barriers to successful adherence. Existing work often attempted to positively influence adherence through methods of reminding or gamifying exercises through VR [11], mixed reality [12], video games [13], or tangible technology [14, 15]. However, these methods were not always as effective with conflicting results and gamified experiences becoming too much of a game.

Integrating exercise into daily activities and objects was already applied to the case of hand rehabilitation in stroke patients [16-18]. Although these studies did not include long-term studies, results were promising overall. However, the attempts to do this for knee patients [19] were too individual and could not be generalised different cases, meaning that there was an area for improvement.

10.2 Prototype compared to requirements list

In **section 5.1**, a requirement list was created to help narrow down approaches and ideas. To evaluate the prototype, it was once again compared to this list to discover any shortcomings. As most requirements were fulfilled, the requirements that were not are discussed below.

Table 10.1 Requirements unfulfilled by current prototype

Ref	Requirement	Discussion
2.3	Could relay progress of knee mobility back to the physiotherapist.	Not fulfilled. This was not prioritised for the final prototype created. However, if the concept is taken further for future development, this can be integrated.
2.12	Must not be rigid or inflexible/ restricting natural knee movements.	Partially fulfilled. The slider was currently too thick, making is slightly uncomfortable to use. This can be easily fixed by making the slider thinner.
4.6	Sensors should be waterproof.	Not fulfilled. This was not a priority for the final prototype created. If the concept is developed further, this can be reevaluated.
5.7	Must be comfortable to use the entire period the tool is being actively used.	Partially fulfilled. Participants noted that the slider was too thick, making sitting slightly uncomfortable. Can be easily fixed by making the slider thinner.

Out of 37 requirements, only 4 were not fulfilled or partially fulfilled, making this prototype successful according to the list. The two requirements that were only partially fulfilled were considered extremely highly important (9 points), so these aspects of the prototype should be fixed. The fix for this is making the slider thinner, which was not yet possible for this prototype due to hardware constraints.

10.2.1 Reconsidering requirements

Looking back at the requirements list after developing the concept further and evaluating it, there are aspects that could be modified to make future research more successful.

With the initial concept designed, more weight can be given to requirements related to daily comfort and ease of use. Both the user evaluations and feedback from physiotherapists noted that the physical comfort of the slider was lacking. In addition to this, a quick daily set up (requirement 2.6, weight 5), might also benefit from a higher weight as some participants in the user evaluations noted that that could be a barrier to consistent daily use.

The importance of a non-gamified experience (requirement 2.14) could also be reworked. The current requirement groups 'foreground' experience and 'gamified' experience. However, in hindsight, this requirement should be split into two. Falling into the background is more important than not being a gamified experience. One physiotherapist had suggested making it more competitive to improve adherence. This could still be an option to investigate further as long as the concept remains in the background.

Finally, the scale used to weight requirements could be updated. Although the weights used range from 2 to 10, many requirements lived in the 8–10 area (22 out of 37 requirements). Making the difference between these three weights clearer might lead to different results. The current scale puts too much focus on distinguishing mid-levels than it does on the high importance levels.

10.3 Prototype compared to the implicit interaction framework

The implicit interaction framework was used to map existing work in **section 3.4** and to discover which ideas in the ideation phase were closest to the desired initiative and attentional demand (**section 5.3.1**). The desired criteria for the concept were for it to fall into the background, while the initiative could be either proactive or reactive.

The concept in the state as tested during the user evaluations and physiotherapist feedback sessions would find itself in the proactive-background quadrant, as shown in **figure 10.1**, putting it in a desired location. It cannot be put far down on the background scale since the lights and vibration, as well as the act of having to do the exercise, does not allow it to fully integrate into the background. However, user tests have shown that it does not require the full attention of the user. Further, the concept is mainly proactive as it reminds the user to move and informs them when they are finished. On the other hand, it is not fully proactive since it also reacts to what the user decides to do.

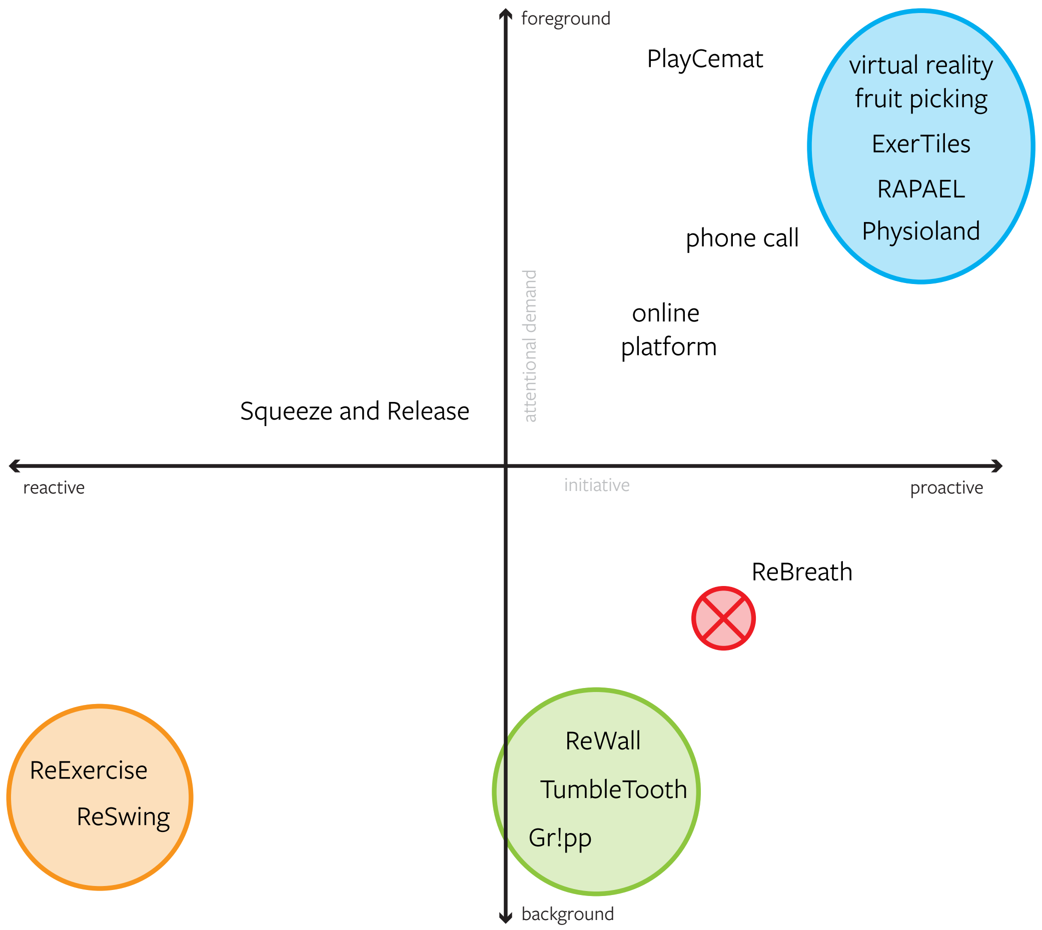


Figure 10.1 Concept (red circle) on implicit interaction framework.

This positioning carries important implications for future design. Currently, the feedback system prevents the prototype from truly integrating into the background. Both the vibration and LED lights draw some focus. An investigation into cues, their levels of intrusiveness and their effect on attentional demand can be done to discover what the best method of feedback is in the case of integration into daily activities.

Further, the reactive-background quadrant remains relatively unexplored. This quadrant might provide an opportunity to design solutions that integrate even more seamlessly into the user's daily routines. A technology that reacts to the user's activity and only prompts when absolutely necessary could allow for a less intrusive experience.

10.4 Suggested improvements to design and concept

Considering both the user evaluations and physiotherapist feedback sessions, several areas for improvement can be identified.

10.4.1 Relevant user group

One of the primary aspects that became clear during the user evaluations was that participants with chronic injuries usually indicated that they would not be inclined to use the prototype. The main reason behind this was the irrelevancy of the exercises. When asked, the physiotherapists agreed with this, mainly seeing it as useful for patients with acute injuries towards the beginning of their treatment plan.

As the participants with chronic injuries said they were more focused on strength training than range of motion, taking inspiration from a different type of exercise may suit their demographic more. One physiotherapist suggested to find a way to add weight to the prototype. This could be done through physically adding weight to the slider, but also through increasing the resistance of the sliding movement. Either different slider options could be made, the slider could have a compartment for extra weight, or the slider could have exchangeable surfaces on the bottom.

While these suggestions would improve the concept, these particular concerns do not indicate that integrating exercises into activities of daily living is not an appropriate approach. Instead, they highlight the necessity of modifying the prototype to better meet the specific needs of different user groups. At home physiotherapy adherence could be improved further if the concept is able to handle multiple types of exercises. This would have to be explored in future research.

10.4.2 Feedback system

A recurring issue that came up in multiple user testing sessions was the missing value of the feedback given by the LED lights. Participants either expected the lights to give feedback on something else, thought they were distracting, or did not notice them at all. The main intention behind the lights was for the user to be able to view how far they managed to extend and flex their knee. However, this feedback could possibly also be communicated in a different way. For example, all feedback could be done through vibration, or the possibility of sound can be investigated.

The above suggestions regarding the LED feedback raises the question whether the mat is a necessary component. The main role of the mat was to house the LEDs as well as provide a smooth surface to slide on. If the LEDs are taken away, a bigger focus can be put on the slider instead. It would require a material that can slide on multiple surfaces, and would be in control of all feedback. This would be more like the 'roller' idea in **section 5.3.3**. At that point in the ideation phase, there was a worry that it would not have added value over a normal roller. However, it could still implement the feedback the users did find valuable.

The participants' reactions highlight the importance of the feedback system when attempting to integrate physiotherapy exercises into daily life, as also mentioned in **section 10.3**. Feedback that is distracting can be too intrusive, acting as a barrier towards full integration.

10.4.3 Slider design and functionality

Both the user evaluations and the physiotherapy feedback sessions flagged issues with the slider. Participants in the user evaluations noted that the slider was too thick to comfortably be used, which was expected, but could not be reduced due to the limitations of the electronics.

A more significant issue was noted by the physiotherapists, where the ankle needs to be able to move to achieve full extension and flexion. The foot needs to both be able to roll onto the heel and the toes. This is currently impossible because the foot is strapped to the slider. However, earlier prototypes showed that not having the foot strapped to the slider made the sliding movement harder since the slider would not always follow.

A redesign could be done to the mat, allowing users to raise their leg to achieve the full extension, but this would compromise on the portability and would make it much larger. Another option would be to once again look into taking away the mat and solely focusing on a slider or roller, as mentioned in the previous section. A roller could possibly provide the space that allows for ankle movement.

These issues do not have as drastic as an effect on integration into daily life as the feedback system, but comfort can still hinder how likely somebody is to continue using the concept. If the users find the prototype comfortable to use, they are more likely to incorporate it into their lives consistently as so also adhere to their at home rehabilitation programs.

10.4.4 Cognitive load and integration into daily life

Finally, the user testing showed that cognitive load is negatively affected when using the prototype. However, the results show differences as fractions of a second. This would suggest that it is possible for the concept not to interfere too much with daily activities. A long-term study with more realistic working conditions would be needed to confirm this. If this shows that the concept does interfere with work, the issue might be with the daily activity the prototype tries to integrate exercise into, and the entire concept would need to be reevaluated.

10.5 Suggested future research

This research has identified multiple areas for further development. Feedback from both user evaluations and physiotherapist feedback sessions showed potential to either narrow down the target group or broaden the capabilities of the prototype. If broadening, options such as adding weight or resistance to the slider may provide an extra challenge.

The feedback system also emerged with areas for improvement. An investigation could be done into alternative feedback methods, focusing on vibration or branching out into other methods, such as sound, to replace the LED lights. This system would have to require the least amount of attentional demand from the user as possible.

Further, future research can also be done into the necessity of the mat. With the removal of the LED-based feedback, the mat may no longer be essential. A more versatile slider design that can function without the mat could be considered. This would also need to consider the comfort and movement range on the ankle.

As mentioned in **section 10.4.4** a long-term study would be required to get better insights into cognitive load. The user testing sessions were artificial with the user having to move their leg for trials instead of time intervals, as well as the arithmetic task not following usual working conditions. Cognitive load may be affected differently during tasks the user does on a regular basis. Further, it would also be valuable to investigate how the effectiveness of the exercise is affected, as a negative affect might mean the concept is not successful.

The lack of long-term study also meant motivation and adherence could not be investigated. While some users said they would like to use the prototype in their daily lives, this cannot be proven without testing it. This would provide further insights into whether users would use them every day, how they would use them, as well as whether it is able to help them prevent stiff knees.

11 Conclusion

The goal was to investigate how an interactive technology object of daily living could be designed to improve at-home physiotherapy adherence for knee injuries. The approach for this was to integrate exercises into daily activities through an interactive technology. Preliminary research into knee injuries, treatment plans, related work in the area of physiotherapy, and interviews with knee injury patients about their daily routines informed the ideation phase. A mat with a slider and vibration clip was proposed to encourage extension and flexion of the knee while the user sits for long periods of time throughout the day.

The final prototype of the concept was tested with people who have knee injuries, as well as shown to physiotherapists for feedback. Cognitive load testing showed that while the prototype slowed down an arithmetic task, the overall dual-task cost was minuscule, meaning integration into daily activities is possible. This, however, requires more testing to be able to draw concrete conclusions from.

Feedback from both the user evaluation and interviews with physiotherapists showed that the concept is most suited for patients with acute injuries at the beginning of their recovery. This is due to chronic injury patients having a bigger focus on strength training than mobility. A way to increase weight or resistance might include the chronic injury group as well.

Participants in the user evaluation noted that the visual feedback given by the prototype was not considered relevant in the context of sitting at a table of desk. Further development of the concept may look into focusing on vibrational feedback as well as possibly omitting the mat completely.

More development is also needed on the slider. Currently, ankle movement is restricted, hindering full extension and flexion. There are multiple remedies that can be investigated, including a redesign of the mat that allows for the user to pick up their foot, a redesign of how the slider is strapped to the foot, and shifting to the possibility of omitting the mat and moving to a roller.

Despite the room for improvement, the approach of integrating physiotherapy exercises into daily activities or objects for knee injuries is promising. More research needs to be done into long-term adherence as well as into the effectiveness of the exercises once they are integrated into an interactive technology. Overall, the concept seems to possibly be useful for knee injury patients to keep in motion throughout the day, preventing stiff knees.

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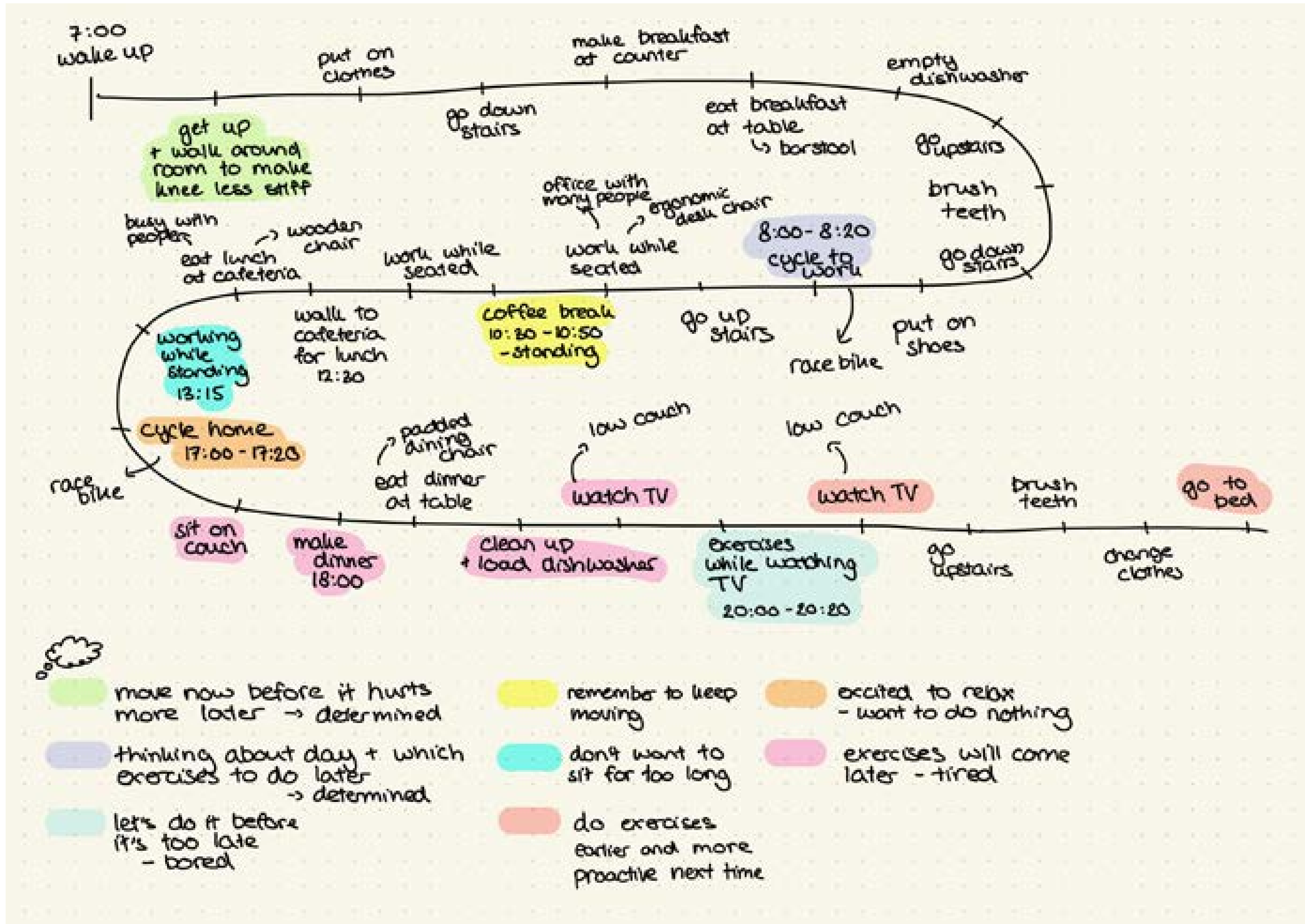
Appendix

Appendix A Patient Interviews

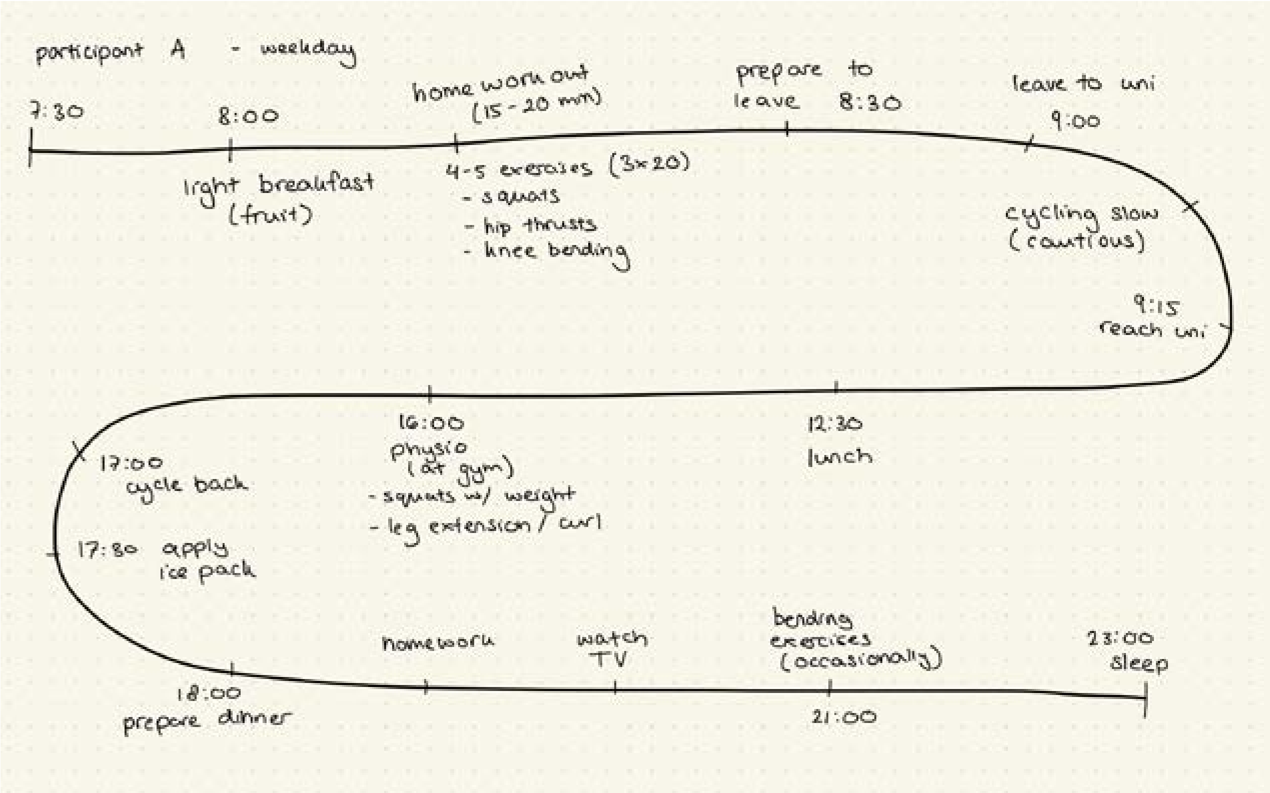
A.1 Example patient interview timeline

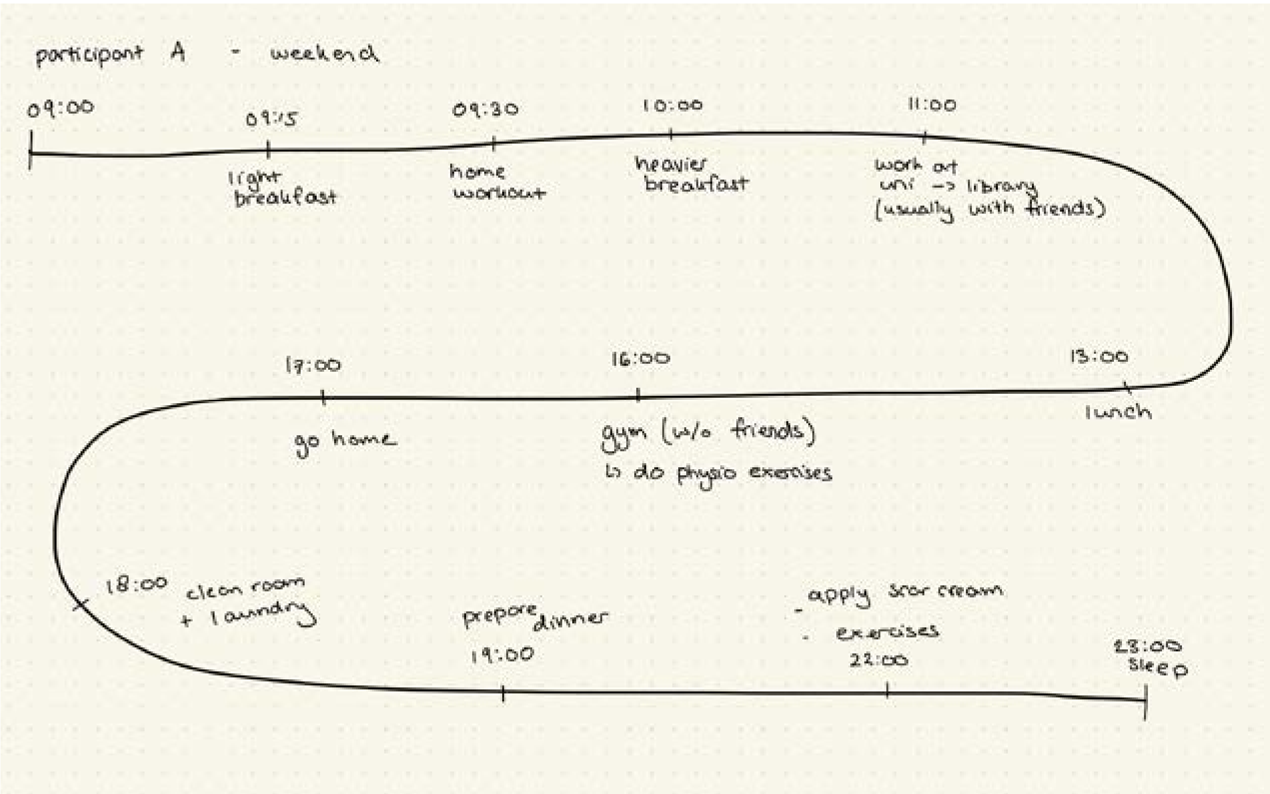


A.2 Patient interview timelines

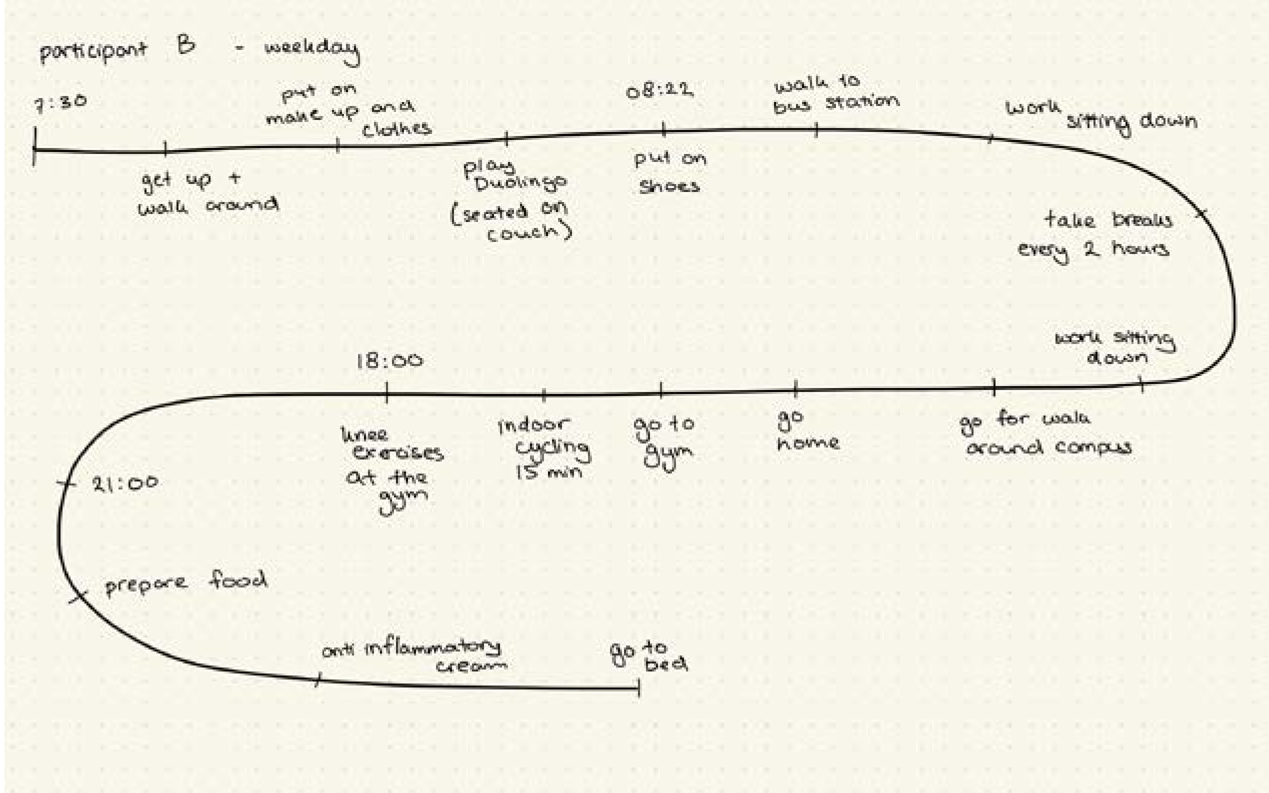
(All handwritten ones remade due to legibility issues. Text is copied directly from the ones the patients made)

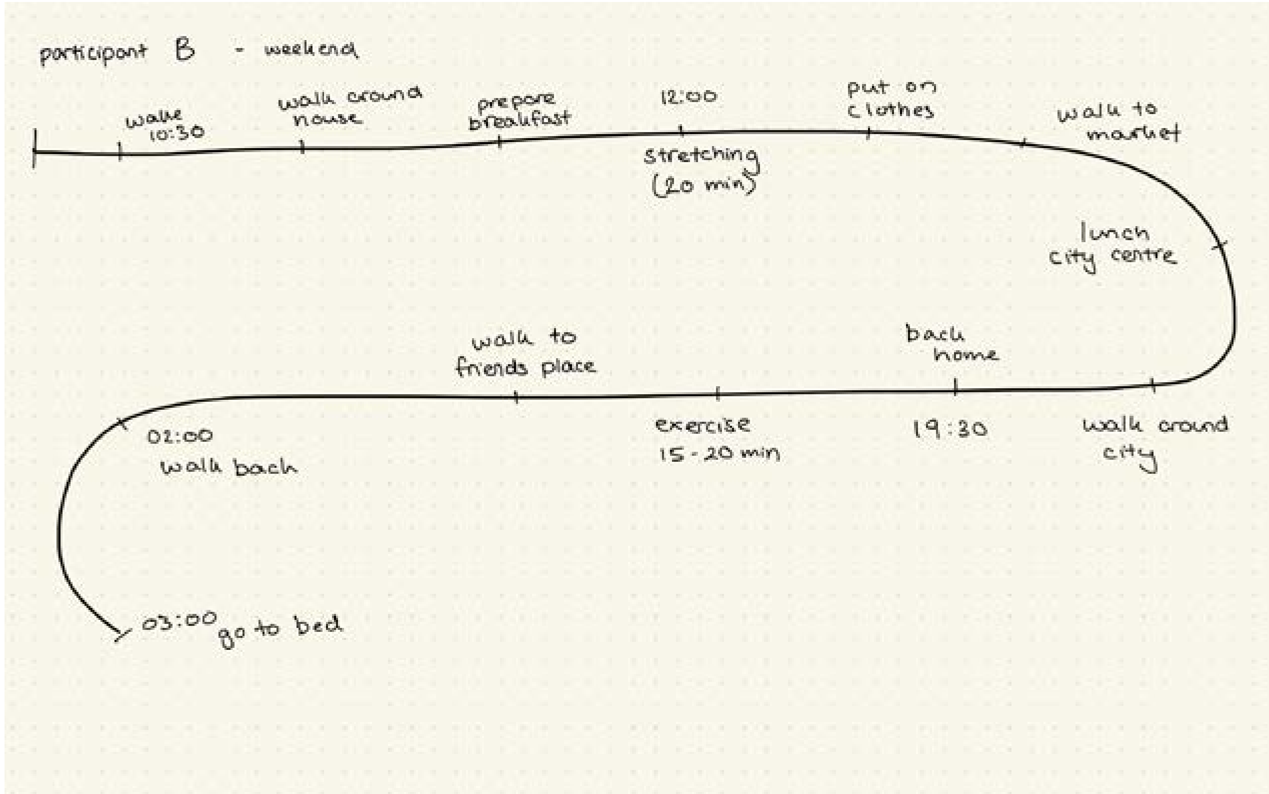
Participant A



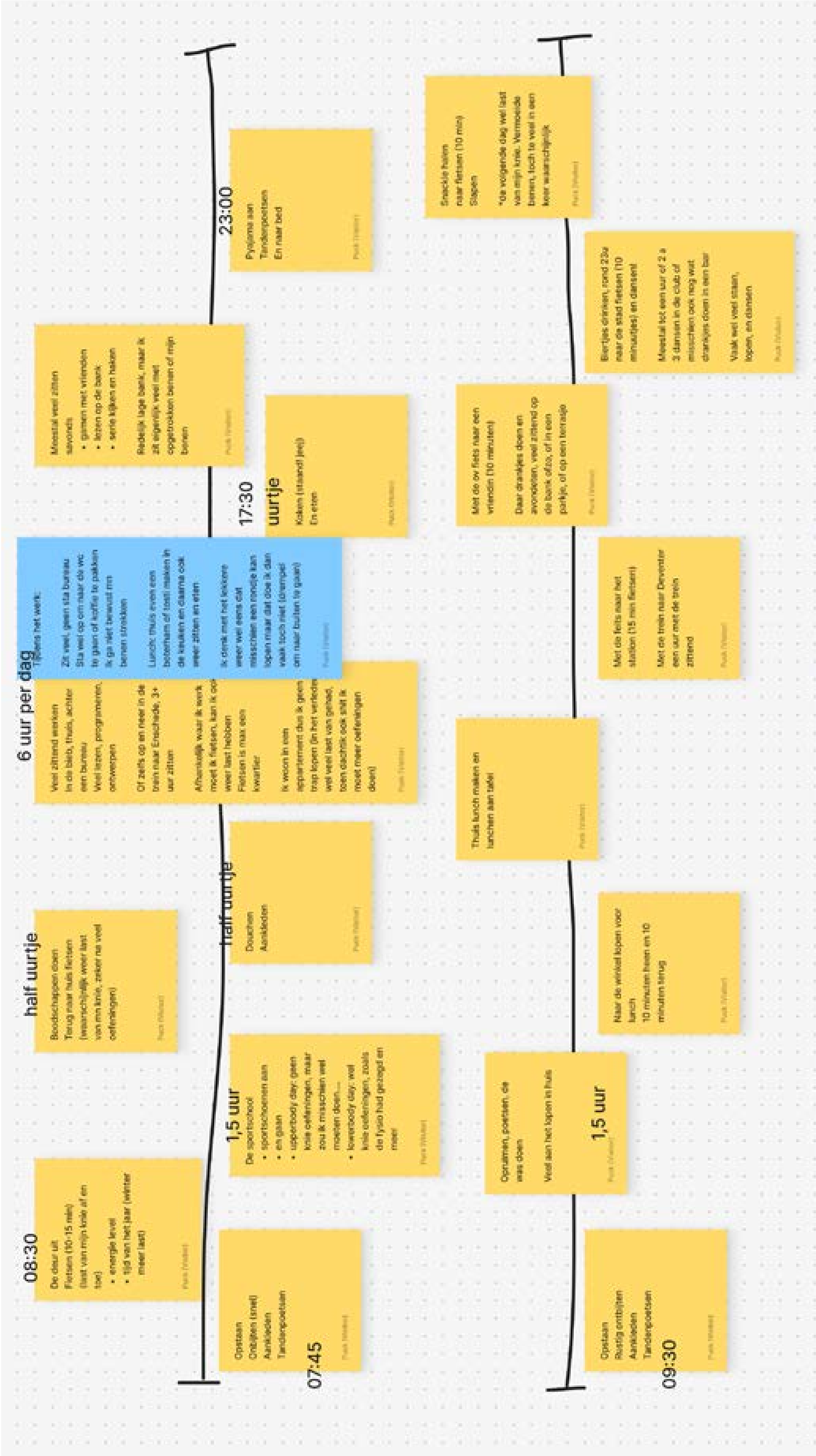


Participant B

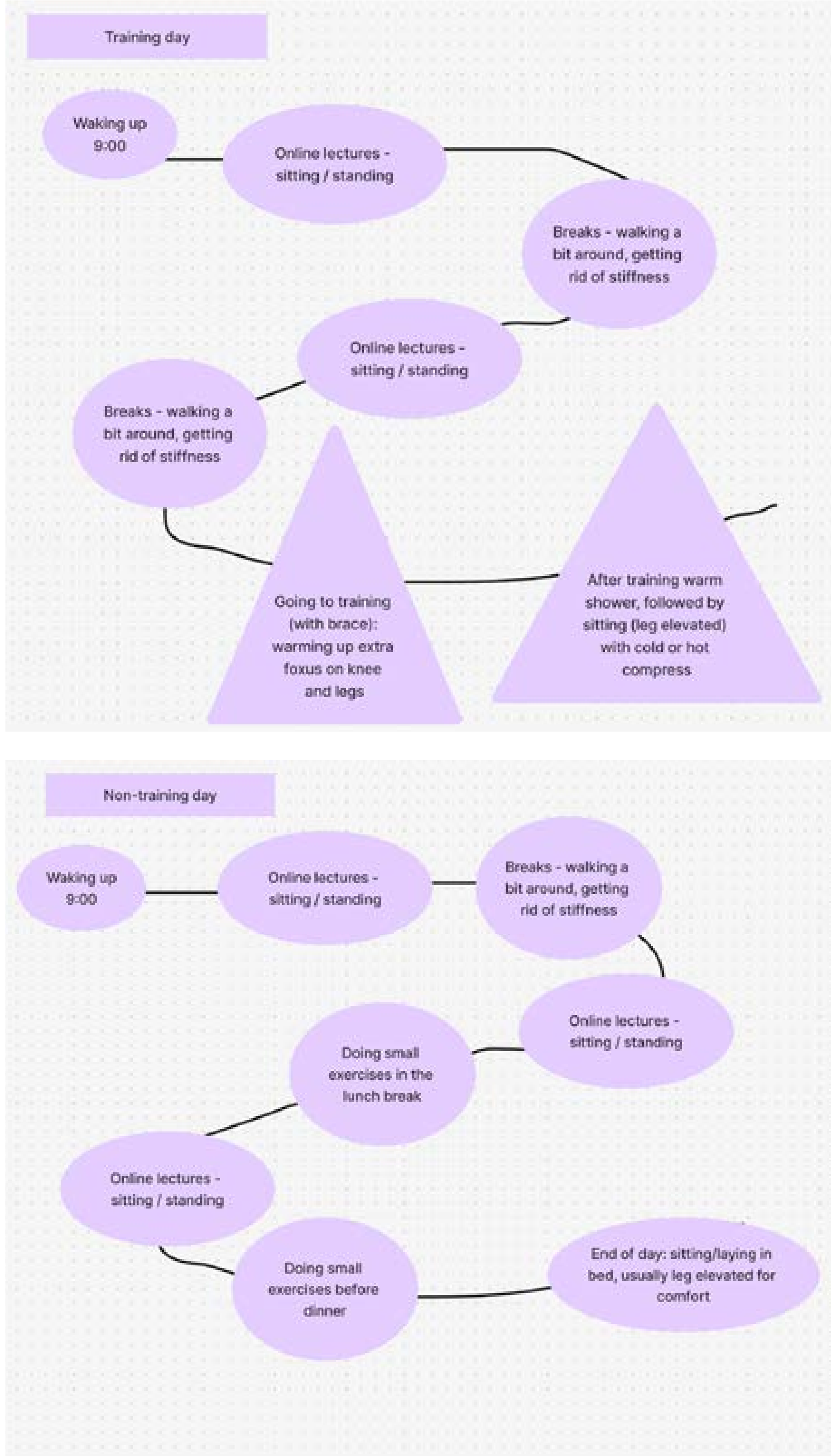




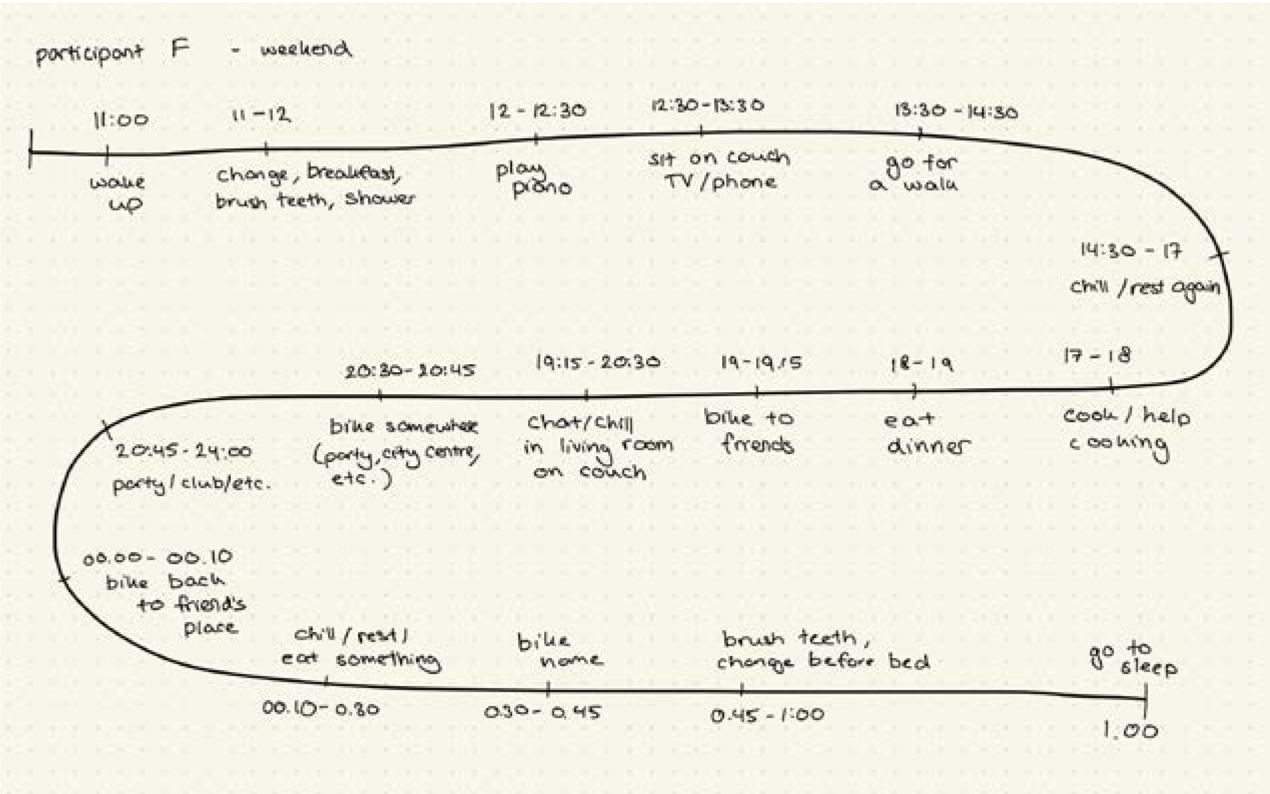
Participant C



Participant D



Participant F



Appendix B List of ideas

Braces/bands/monitors

1. Smart knee brace with sensors that track knee movement
2. Smart knee brace that tracks the degree of knee bending and straightening and gives audio alerts if the user is not achieving full range of motion.
3. Smart knee brace as above but with vibration queues.
4. Wearable band with sensors that track knee movement
5. A wearable band that provides haptic feedback about range of motion and gait as somebody is walking.
6. Activity monitor that can be clipped onto clothing. Tracks movement throughout the day and vibrates when it's time to move again.
7. Brace that helps slowly start moving again after long period of inactivity. It expands and contracts to help to flexing and extending motion.
8. Brace that warns when the user has moved their knee too much.
9. Monitor that specifically tracks motion up and down steps/stairs and encourages the proper flexing/extending through haptic feedback.
10. Monitor that freezes a device being used (laptop/phone/etc.) until the user moves.
11. Knee brace that tracks and shows real-time knee flexion/extension
12. Monitor to clip onto shoelaces/shoes that tracks knee movement
13. Clip on a keychain that can track movement

Clothing

14. Leggings that track knee motion
15. Socks that track knee and leg motion
16. A belt that can track when somebody is moving as well as their knee motion and gives feedback during inactivity
17. Trousers with built in resistance bands that help guide the knee through full range of motion.
18. Wearable anklet that tracks knee/leg motion
19. Leggings with compression in certain areas that make knee bending and flexing easier/harder.
20. Hidden knee support brace integrated in jeans

Shoes

21. Shoes designed to give feedback (vibration) on knee flexing and extending that also tracks knee movement – specifically while walking/moving
22. Shoes designed to give feedback (visual through LEDs) on knee flexing and extending that also tracks knee movement – specifically while walking/moving
23. Shoes designed to encourage knee stability while tracking movement and motion – specifically while walking/moving
24. Shoes designed to encourage knee flexing and extending that also tracks knee movement – specifically while resting/sitting
25. Smart insoles to put in shoes that can track movement

26. Shoes with sole designed to encourage movement (think of those shoes that were made to enhance walking exercises)
27. Shoes designed with a sole that requires a slight knee bend to engage, for knee flexion and extension during walking.
28. Shoe kind of like heelys (wheel in sole at heel) to make extending/flexing while sitting smoother.
29. Move around edge of shoe on floor to move around knee. Shoe gives a reminder, user does it, shoe tracks movement throughout day.
30. Doing arc quad exercises/extension & flexion when putting on the shoe. The shoe requires you to make the movement.
31. Standing on your toes/calf raise when reaching for things higher up, the shoes recognises this movement.
32. Shoes that project a path onto the floor that the user must follow, practicing different step sizes for different levels of extension/flexion. Only does this when people haven't moved enough yet.

Furniture

33. A smart mat that encourages and tracks knee movement when sitting
34. A cushion to use when elevating and extending the knee that encourages the user to occasionally move around
35. A chair that tracks knee posture and encourages the occasional stretching
36. Floor lamp that can track when somebody is moving/sitting for too long
37. A footrest that promotes proper resting as well as movement
38. Bed frame that analyses knee movement when getting up
39. Cupboard that encourages people to do calf raises by having a shelf higher up.
40. Chair that moves backwards and forwards slowly while user keeps their foot still, helping extend/flex knee while sitting.
41. Lower cupboards that should be closed with the foot/leg. Area lights up that requires contact when closing.
42. A chair that requires to be moved backwards and forwards slowly, encouraging user to extend/flex knee
43. Bedside step that guides user through extension/flexion as they get out of bed.
44. Chair that can change its ergonomics based on the user's knee movement
45. Rolling footrest that allows somebody to flex and extend their knee as they are sitting and doing something else.
46. Coffee table with leg lift mechanism.
47. Pedal sink. Have to do step up motions with knee and push down for water to come out of faucet.
48. Coffee table that can be spun around with the legs, encouraging movement in the knee.
49. Trash can pedal that requires large pushing down motion with leg.
50. Tiles to put on stairs that make you climb and descend the stairs in a certain way.
51. Carpet for living room at couch that lights up in certain spots until somebody moves their foot onto it.

Other daily objects

52. Knee massager (?)
53. A bicycle seat that can track motion
54. Bicycle pedals that can track motion
55. A cup that can be taken along during coffee breaks to look at how often somebody stands up and moves
56. Bathmat with embedded sensors that get activated when somebody stands on it and can tracks the movement
57. A bag that moves away, forcing the user to get up and walk to get to it
58. Ball to put on the floor that the user has to kick/push away with foot. It can roll to different locations in set area. Specifically designed to use underneath a desk while sitting at it.
59. Sofa cushion that will vibrate until the user has moved their leg.
60. Pedal to put underneath desk for constant movement. Resistance can be increased if muscles should be strengthened as well.
61. A door handle that requires help from the leg to be opened instead of the hand.
62. Bicycle that puts the focus on the injured leg (do most of the work with the bad knee instead of the good knee)
63. Shoehorn that guides user to bend knees when putting on shoes.
64. Bicycle that allows you to adjust the seat height based on the flexion/extension angles you desire.
65. Vacuum cleaner that has an adjustable height. It tracks pushing/pulling motions, encouraging users to bend their knees to certain degrees.
66. Standing mirror that can track motion and shows a user which exercises to do as they're getting ready

Uncategorised/general ideas

67. Something that encourages you to use your bad knee instead of avoiding it
68. Walking on edge of sidewalk
69. Shopping cart handle clips that tracks knee extension and flexion when shopping.
70. Kneeling pad for tasks done on knees to provide extra comfort.

Exception cases

71. Electrician: a step stool or ladder that has adjustable step/rung heights.
72. Driver: car seat adjuster that checks the angle of the knee periodically and notifies the driver when they should sit with their knee at a different angle.
73. Driver: interactive pedal covers that are able to check the angle of flexion/extension

74. Office worker: a standing desk that adjusts its height throughout the day, making users extend and flex their knees along with it.
75. Construction worker: a ladder that uses leg controls to move and change height.
76. Driver: a seat cushion that provides feedback on posture and prompts to do knee stretches during breaks.
77. Delivery driver: changing step height from van to floor, causing the user to step up and down with different flexion/extension angles.
78. Hairdresser: salon chair with pedal that requires more knee flexion/extension than current salon chairs.
79. Hairdresser: stool for hairdresser that requires certain leg/knee movements to be able to roll around.
80. Flight attendant: hand luggage that is pulled by legs instead of the hand.
81. Flight attendant: height adjustable trolley that encourages user to bend over to grab things.
82. Cashier: control the conveyer belt with leg movements. Flexing knee makes it move, extending knee makes it stop.
83. Chef: an oven door that is closed and opened with the feet instead of hands.
84. Artist: and easel that forces the user to work at different heights, meaning the need to stand, sit, and kneel for different heights.
85. Piano player: piano pedal with more resistance.
86. Guitar player: guitar pedal board that requires knee bends to activate effects, promoting knee flexion and extension during guitar playing.
87. Drummer: A hi-hat pedal that provides more resistance than normal.
88. Musician: instead of tapping along with the beat with foot, move the entire leg to activate a metronome sound. Tracking done through an anklet.
89. Photographer: adjustable tripod that changes height based on knee movements.
90. Gardener: a gardening stool that helps user bend their knees in a safe way rather than kneeling all day.

Toolkits

91. A toolkit of sensors that can be placed on different pairs of shoes (can be combined with the other ideas in shoes section)
92. A toolkit of sensors that can be placed on different clothes (can be combined with the other ideas in clothing section)
93. Walking toolkit that combines insoles for shoes and a wearable band
94. Chair toolkit that can be placed on different chairs and is able to recognise inactivity and encourage the used to move around.
95. Cushion cover that can be put around different cushions. Can combine with cushion ideas.
96. Furniture slider. A 'slider' that can be attached to different types of furniture (table legs, chairs, bookshelves, etc.) allowing somebody to extend and flex their knee while around this furniture.
97. Mat overlay. An overlay to put on existing mats and shows how a user should move their leg to encourage knee movement.
98. A pedal that can be transported and used in different contexts: at a desk, at the dining table, while sitting on the couch.
99. Buttons that can be put around in the user's environment. They press the button, registering that they've been there, meaning they have moved around.
100. Platforms that can be placed around in the user's environment, such as at a bed or in the hallway, making the patient to a step up and step down as they walk around in the environment.

Appendix C Ideas x requirement list points

		User interaction functionality requirements																Knee functionality requirements					Safety							Usability requirements									
		1.1	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	2.10	2.11	2.12	2.13	2.14	2.15	3.1	3.2	3.3	3.4	3.5	4.1	4.2	4.3	4.4	4.5	4.6	4.7	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	
es/bands/mo	1	x	x			x				x						x		x		x	x									x	x	x	x		x				105
	2	x	x	x		x	x			x						x		x	x	x	x									x	x	x	x		x				116
	3	x	x	x		x	x			x						x		x	x	x	x									x	x	x	x		x				116
	4	x	x			x				x	x			x	x	x				x	x									x	x	x	x	x	x	x			128
	5	x	x	x		x	x			x	x			x	x	x			x	x	x									x	x	x	x	x	x	x	x		155
	6	x	x	x		x	x			x				x	x	x			x	x	x									x	x	x	x	x	x	x	x		145
	7	x	x			x	x			x	x					x	x	x	x	x	x									x	x	x	x		x				128
	8	x	x	x		x	x			x						x		x		x	x									x	x	x	x		x				106
	9	x	x	x		x	x			x	x			x	x	x		x		x	x									x	x	x	x	x	x	x			148
	10	x		x		x				x	x			x	x	x			x	x	x									x	x	x	x	x	x	x	x		145
	11	x	x			x	x			x						x				x	x									x	x	x	x		x				88
	12	x	x			x				x	x			x	x	x				x	x									x	x	x	x	x	x	x	x		135
	13	x	x			x				x	x			x	x	x				x	x									x	x	x	x	x	x	x	x		135
clothing	14	x	x			x				x	x			x	x	x				x	x									x	x	x	x	x	x		x		126
	15	x	x			x				x	x			x	x	x				x	x									x	x	x	x	x	x	x	x		135
	16	x	x	x		x	x			x	x			x	x	x			x	x	x									x	x	x	x	x	x	x	x		155
	17	x				x	x			x	x					x	x	x	x	x	x									x	x	x	x	x	x				124
	18	x	x			x				x	x			x	x	x				x	x									x	x	x	x	x	x	x	x		135
	19	x				x	x			x	x					x	x	x		x	x									x	x	x	x	x	x		x		121
	20	x				x	x			x	x					x	x	x		x	x									x	x	x	x	x	x				114
shoes	21	x	x	x		x	x			x	x			x	x	x				x	x									x	x	x	x	x	x	x	x		145
	22	x	x	x		x	x			x	x			x	x	x				x	x									x	x	x	x	x	x	x	x		145
	23	x	x			x	x			x	x			x	x	x				x	x									x	x	x	x	x	x	x	x		137
	24	x	x			x	x			x	x			x	x	x			x	x	x									x	x	x	x	x	x	x	x		147
	25	x	x			x				x	x			x	x	x				x	x									x	x	x	x	x	x	x	x		135
	26	x				x	x			x	x			x		x		x	x	x	x									x	x	x	x	x	x				123
	27	x	x			x	x			x	x			x		x	x	x	x	x	x									x	x	x	x	x	x		x		148
	28	x				x	x			x	x			x		x	x	x	x	x	x									x	x	x	x	x	x		x		140
	29	x	x	x			x			x	x			x	x	x	x	x	x	x	x									x	x	x	x	x	x	x	x		166
	30	x					x			x	x				x	x	x	x		x	x									x	x	x	x	x	x	x	x		131
	31	x	x			x	x			x	x				x	x	x	x		x	x									x	x	x	x	x	x	x			141
	32	x		x			x			x	x			x		x	x	x	x	x	x									x	x	x	x		x	x	x		144
furniture	33	x	x				x			x	x			x	x	x		x		x	x									x	x	x	x		x	x	x		134
	34	x		x		x	x			x	x			x	x	x				x	x									x		x		x	x	x			119
	35	x	x	x		x	x			x	x			x	x	x				x	x									x				x	x	x	x		121
	36	x	x			x	x			x	x			x	x	x				x	x									x				x	x	x	x		122
	37	x					x			x	x			x	x	x				x	x									x				x	x	x			98
	38	x				x				x	x			x	x	x				x	x									x				x	x	x	x		112
	39	x					x			x	x			x		x		x		x	x													x	x	x	x		98
	40	x				x	x			x	x			x	x	x	x	x	x	x	x									x				x	x	x	x		144
	41	x					x			x	x			x		x	x	x		x	x									x				x	x	x	x		115
	42	x					x			x	x			x	x	x	x	x	x	x	x									x				x	x	x	x		135
	43	x				x	x			x	x			x	x	x				x	x									x					x	x	x		110
	44	x					x			x	x			x	x	x	x			x	x									x				x	x	x	x		115
	45	x					x			x	x			x	x	x	x	x	x	x	x									x					x	x			124
	46	x				x	x			x	x			x	x	x	x			x	x									x				x	x	x	x		124
	47	x					x			x	x			x		x	x	x		x	x									x				x	x	x	x		115
	48	x					x			x	x			x	x	x	x	x		x	x									x				x	x	x	x		125
	49	x				x	x			x	x			x		x	x	x		x	x									x				x	x	x	x		124
	50	x					x			x	x			x	x		x	x		x	x									x		x		x	x	x	x		122
	51	x					x			x	x			x	x		x	x		x	x									x					x	x	x		114
other	52																																						0
	53	x	x			x				x	x			x	x	x		x		x	x									x	x		x	x	x		x		132
	54	x	x			x				x	x			x	x	x		x		x	x									x	x		x	x	x		x		132
	55	x				x				x	x			x	x	x			x	x	x									x	x	x	x	x	x	x	x		137
	56	x	x			x				x	x			x	x	x				x	x									x		x		x	x	x	x		124
	57	x					x			x	x			x		x	x			x	x									x	x	x	x		x	x	x		116
	58	x					x			x	x			x	x		x	x		x	x									x	x	x	x	x	x	x	x		133
	59	x		x		x	x			x	x			x	x	x				x	x									x				x	x	x			115
	60	x					x			x	x			x	x	x	x	x	x	x	x									x	x	x	x	x	x		x		141
	61	x					x			x	x					x	x			x	x									x				x	x	x	x		96
	62	x				x	x			x	x			x	x	x	x	x		x	x									x	x		x	x	x		x		136
	63	x				x	x			x	x				x	x	x	x		x	x									x	x	x	x	x	x	x	x		140
	64	x	x			x	x			x	x			x	x	x	x	x		x	x									x	x		x	x	x		x		144
	65					x	x			x	x			x		x	x	x		x	x									x				x	x	x	x		114
	66	x					x			x	x			x	x	x	x	x		x	x									x				x	x	x	x		125
uncategorise	67																																						0
	68																																						0
	69		x			x	x			x	x			x	x	x	x	x		x	x									x	x	x	x	x	x	x	x		147
	70					x	x			x				x		x	x			x	x									x	x	x	x	x	x	x	x		109
xception case	71	x				x	x			x	x			x		x	x	x		x	x									x	x				x		x		119
	72	x	x	x		x	x			x	x			x		x			x	x	x									x					x	x	x		126
	73	x	x			x	x			x	x			x	x	x		x		x	x									x	x	x	x	x	x	x	x		147
	74	x				x	x			x	x			x		x	x	x	x	x	x									x			x		x		x		124
	75	x					x			x	x			x		x	x	x	x	x	x									x	x		x		x	x	x		132
	76	x	x	x		x	x			x	x			x		x			x	x	x									x	x	x	x	x	x	x	x		145
	77	x				x	x			x	x			x	x	x	x	x	x	x	x									x			x		x		x		134
	78					x	x			x	x			x	x	x	x	x	x	x	x									x			x		x	x	x		133
	79	x	x			x	x			x	x			x	x	x	x	x	x	x	x									x	x		x		x		x		150
	80						x			x	x					x	x			x	x									x	x	x	x	x	x		x		92
	81					x	x			x	x			x	x	x	x			x	x									x			x		x		x		104
	82						x			x	x			x	x	x	x	x	x	x	x									x			x		x	x	x		124
	83	x					x			x	x			x	x	x	x	x	x	x	x									x			x		x	x	x		134
	84					x	x			x	x			x	x	x	x	x	x	x	x									x			x		x		x		124
	85					x	x			x	x			x	x	x	x	x		x	x									x			x		x	x	x		123
	86					x				x	x			x	x	x	x	x		x	x									x	x	x	x	x	x	x	x		137
	87					x				x	x			x	x	x	x	x		x	x									x	x		x		x	x	x		129
	88		x			x	x			x	x			x	x	x	x	x		x	x									x	x	x	x	x	x	x	x		147
	89									x	x			x	x	x	x	x	x	x	x									x	x	x	x	x	x	x	x		138
	90					x	x			x	x			x	x	x	x	x	x	x	x									x	x	x	x	x	x	x	x		149
toolkit	91	x	x	x		x				x	x			x	x	x				x	x									x	x	x		x		x	x		137
	92	x	x	x		x				x	x			x	x	x				x	x									x	x	x		x		x	x		137
	93	x	x	x		x				x	x			x	x	x				x	x									x	x	x		x		x	x		137
	94	x	x	x		x	x			x	x			x	x	x			x	x	x									x	x	x		x		x	x		149
	95	x	x	x		x	x			x	x			x	x	x				x	x									x	x	x	x	x	x	x	x		145
	96	x				x	x			x	x			x	x	x	x	x	x	x	x									x	x	x	x	x	x	x	x		159
	97	x					x			x	x			x	x	x	x	x	x	x	x									x	x	x	x	x	x	x	x		150
	98	x					x			x	x			x	x	x	x	x	x	x	x									x	x	x	x	x	x	x	x		150
	99	x		x						x	x			x	x	x	x		x	x	x									x	x	x		x	x	x	x		143
	100	x				x	x			x	x			x	x	x	x	x		x	x									x			x		x	x	x		133
	maze	x	x	x		x	x			x	x			x	x	x	x	x	x	x	x									x			x		x	x	x		
	roller	x	x	x		x	x			x	x				x	x	x	x	x	x	x									x	x	x	x	x	x	x	x		
		640	256	120	0	423	106	0	0	670	600	0	0	486	460	448	320	370	190	603	536	0	0	0	0	0	0	0	9	462	352	172	132	220	201	441	357	0	

Appendix D Questionnaires used during user evaluation

NASA task load index

Figure 8.6

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Page 1 of prototype feedback questionnaire

Prototype feedback questionnaire

1. Feedback

The feedback provided by the prototype was **helpful**:

Strongly Disagree			Neutral			Strongly Agree
☐	☐	☐	☐	☐	☐	☐

The feedback was **easy to understand**:

Strongly Disagree			Neutral			Strongly Agree
☐	☐	☐	☐	☐	☐	☐

The feedback was **relevant**:

Strongly Disagree			Neutral			Strongly Agree
☐	☐	☐	☐	☐	☐	☐

2. Usability

The prototype was **easy** to use:

Strongly Disagree			Neutral			Strongly Agree
☐	☐	☐	☐	☐	☐	☐

I found the prototype to be **clear** to use (not confusing):

Strongly Disagree			Neutral			Strongly Agree
☐	☐	☐	☐	☐	☐	☐

Page 2 of prototype feedback questionnaire

The prototype was **intuitive** to use:

Strongly Disagree			Neutral			Strongly Agree
□	□	□	□	□	□	□

The prototype was **not distracting** to use:

Strongly Disagree			Neutral			Strongly Agree
□	□	□	□	□	□	□

3. Integration into daily life

I would consider **using this prototype in my daily life**:

Strongly Disagree			Neutral			Strongly Agree
□	□	□	□	□	□	□

What were the biggest challenges or frustration while using the prototype?

What features or improvements would you like to see added to the prototype?

Are there any specific use cases or scenarios where you think the prototype would be particularly valuable?

Appendix E Statistical results

E.1 ANOVA results average time taken

Tests of Between-Subjects Effects

Dependent Variable: average_time

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	36.885[a]	19	1.941	15.852	<.001
Intercept	372.909	1	372.909	3044.944	<.001
trial_type	.665	1	.665	5.427	.022
participant	34.382	9	3.820	31.193	<.001
trial_type * participant	1.839	9	.204	1.668	.110
Error	9.797	80	.122		
Total	419.592	100			
Corrected Total	46.683	99			

a. R Squared = .790 (Adjusted R Squared = .740)

E.2 Average time taken per participant

Descriptive Statistics

Dependent Variable: average_time

trial_type	participant	Mean	Std. Deviation	N
dual	1	2.8760	.34804	5
	2	2.4580	.50672	5
	3	1.7240	.16994	5
	4	2.8380	.69001	5
	5	1.4400	.18615	5
	6	1.6600	.25817	5
	7	1.0126	.14969	5
	8	2.4132	.20203	5
	9	2.1156	.32284	5
	10	1.5887	.18283	5
	Total	2.0126	.67457	50
single	1	2.3120	.63464	5
	2	1.8980	.24325	5
	3	1.5300	.28914	5
	4	3.0660	.51916	5
	5	1.4440	.34268	5
	6	1.3560	.16502	5
	7	.8444	.09123	5
	8	2.1483	.43709	5
	9	2.3999	.29543	5
	10	1.4971	.13386	5
	Total	1.8496	.69578	50
Total	1	2.5940	.56675	10
	2	2.1780	.47700	10
	3	1.6270	.24586	10
	4	2.9520	.58808	10
	5	1.4420	.25999	10
	6	1.5080	.25961	10
	7	.9285	.14671	10
	8	2.2807	.35006	10
	9	2.2577	.32796	10
	10	1.5429	.15859	10
	Total	1.9311	.68669	100

E.3 Average dual task cost

Participant	Time	Error	Average cost
1	0.02	-0.02	0.000
2	1.00	-0.13	0.436
3	0.35	0.00	0.175
4	-0.41	-1.53	-0.968
5	-0.01	0.00	-0.005
6	0.55	0.00	0.274
7	0.30	0.00	0.150
8	0.71	-0.51	0.102
9	0.20	0.00	0.099
10	0.10	1.00	0.552
			0.082