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DEVELOPMENT OF A

SMART HEALTHCARE TRACKING SYSTEM

FOR THE HIP FRACTURE REHABILITATION PROCESS

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Creative Technology BSc.

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Abstract

Hip fractures are a common problem of an aging population as the incident rate within elderly groups of people is significantly higher compared to younger people. Even with proper treatment the mortality rate after one year can be up to 30%. In order to improve the quality of care during the rehabilitation, telemonitoring was researched as an option by the Ziekenhuisgroep Twente. This paper researches the possibility of *how a head worn health tracking device could be implemented in the hip-fracture rehabilitation process* and in this matter proposes a concept of a telemonitoring device easily applicable to any glasses. The device sits on the inside of the handle and monitors heart rate, heart rate variability and steps and can therefore deliver qualitative data to. During the evaluation the use of pulse oximetry proved problematic, resulting in a good ICC for HR but only in a weak ICC for HRV when compared to the reference measurements. The correlation would differ significantly when being active compared to being at rest, when HRV reached a moderate correlation. The number of steps could be recognized with a positive error of 20%, which is less problematic as they are only a measure of activeness.

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I - Introduction

In the last 117 years alone the global average life expectancy has more than doubled and came close to 70 years. However, with increasing age there are new, age related challenges to face and existing ones grow larger and larger, one of them being hip fractures.
In 2004 there were about 140.9 (per 100.000) incidents in Germany alone, which is an increase of 16.3% compared to 1995 (Icks, Haastert, Wildner, Becker and Meyer [2008]).
The main problem these patients are facing is gaining trust into their own abilities again, as, even though if correctly treated the bodies functionality is almost fully restored to the level from before the accident, patients do not trust their capabilities anymore and become bedridden and only leave their bed when told to by their physiotherapist, leading to an observed mortality rate ranging between 20 and 30% within the first year (Schnell, Friedman, Mendelson, Bingham and Kates [2010]), mostly due to circulatory and respiratory diseases, which can be caused by inactive patients staying in bed for long. To deliver better care to these patients, information about their daily activity is a great support for therapists, giving a better understanding of motivations and activities.

Today's smart devices like smartwatches or fitness trackers cannot only help the therapist with this information but can potentially even help motivate them by themselves. However, especially the above-mentioned devices have several disadvantages, as sometimes activity can be falsely tracked when used in combination with aids like walkers or wheelchairs. Furthermore, as the patients often are of old age, some suffering from Alzheimer or are in Delirium, they have problems with unknown devices attached to them. A smart textile can solve these problems by using sensors elegantly hidden in the clothing. Therefore, in this paper different ways of implementing such a system in the healthcare sector for elderly people will be researched and an answer to the question "*How can a smart system for monitoring elderly hip patients be implemented*?" will be searched for.

For this it is necessary to first conduct a literature research on the recent developments and findings of smart textiles in the health sector. Secondly, stakeholders will be identified and analyzed and a set of requirements resulting from the previous findings will be established. Furthermore, existing, commercialized solutions searched for and be compared with each other with respect to the research question and the established requirements.

II - Literature Findings

In the following section, a literature research will be conducted on the previously mentioned research question. For this, a definition of the term 'smart textile' needs to be established first and a general overview will be given. Next, it will be looked at which body signals are interesting and feasible to measure with such a system. Third, the latest developments in sensors, that made the movement of smart textiles possible, will be explored and potential sensors will be looked at. Another important question to dive into is the placing of the system on the body, as several signals need to be measured in one spot.

2.1 - 'Smart Textile'

Within the last century, Smart technology has successfully become one of the key technologies of the current century. But what makes a technology smart? According to IGI Global, a technology that "allow[s] sensors, databases, and wireless access to collaboratively sense, adapt, and provide for users within the environment" can be called 'smart'. In combination with textiles, this definition can be extended to the one of Rijavec (2009), who also calls smart textiles "active textiles". She states that a smart textile "react[s] or adapt[s] to the changes in the environment as a result of integrated active functional materials, smart materials or active systems". Hertleer, van Langenhove and Puers (2006) note four different levels of the above-mentioned integration into fabric, the first one simply being able to "adapt to clothes (i.e. a pocket to hold a mobile phone)". The second level then integrates electronics such as sensors into clothes as connectable modules. On the third level, active systems are being integrated, woven displays are given as an example. The last level of integration, active fibers, such as transistors or diodes, being the micro-electronic building blocks, is said to need substantial development to commercialize it.

In the following, these definitions will be used as a guideline when investigating the possibilities of implementations of a textile based smart healthcare device.

2.2 - Body Signals

In order to support the rehabilitation phase of hip fracture patients, the system is meant to read several body signals, that can be supportive for doctors and therapists. For this, it will be looked at research on textile based healthcare systems in the rehabilitation sector.

To begin with the most basic body signal, the heart rate (HR) is one of the main functions keeping the body alive. In their research, Servati, Zou, Wang, Ko and Servati (2017) note that most monitoring systems keep track of it. Changes in heart rate (HR) happen frequently for example due to body exercises and can therefore have a variety of physiological and pathological causes. However, it can be a direct mirror of body-wellbeing. Furthermore, the heart rate variability (HRV), which is measured by looking at the small, short-term changes in heart frequency, can change over time and is influenced by physical and mental conditions. A medical, textile-based system proposed by Paradiso, Loriga and Taccini (2005), which aims at patients with heart disease, also tracks the heart rate by use of an electrocardiogram, as a precise measurement had to be taken. Another textile sensor system was proposed by Rai et al (2012) and aimed to deliver cardiac health monitoring to patients with chronic health conditions, recuperating patients and safety of personnel in high risk jobs. For this purpose, heart rate and heart rate variability were being tracked amongst others by sensors integrated in a shirt.

A second artifact closely related to heart rate and the blood flow is the blood pressure. According to Rai et al. (2012), it is an important signal in the cardiac monitoring field. Furthermore, also Servati et al. (2017) note blood pressure to be one of the most common signals measured. This is because with high blood pressure the danger of cardiovascular diseases rises as well. However, it is not being included in the system of Paradiso et al. (2005). All in all, blood pressure can be considered an important artifact for risk analysis. It is however not included in the majority of smart systems, which can be because of the inconvenient way of measuring.

Third, the respiration rate can be said to be vital to the human body. It has been observed by Servati et al. (2017), that the respiratory rate can give valuable indicators of cardiopulmonary diseases and even hint other diseases or conditions depending on the placement of the respiratory sensor on the body. Also Paradiso et al. (2005) included an respiration monitor into their smart shirt. On the contrary, the system by Rai et al. (2012) did not include respiration rate. But being tailored for cardiac monitoring, this was to be expected. To conclude, respiration seems to be beneficial if the overall health status is being monitored closely but may be disregarded if a more narrowed picture is preferred.

The fourth signal that can be monitored is the skin temperature. Servati et al. (2017) observe Body temperature (T) to be a commonly used indicator for diseases, while also other critical conditions such as blood depletion conditions or toxins can lead to a change in body temperature. This choice is supported by Paradiso et al. (2012), who integrated a temperature sensor as well, while Rai et al. choose to disregard it. Similar to the respiration rate, temperature seems to be more interesting to more general systems.

Lastly, as stated by Panula et al (2011), some of the main causes of death after a hip fracture are malignant neoplasms, circulatory diseases and respiratory diseases, which often can be caused by laying in a bed for too long. But also, the two main postoperative, non-lethal complications, urinary tract infection and pressure sores, as observed by Obrant (1996), are commonly found in bedridden patients. Hence the activity can be considered an important fact to be monitored. This is also supported by Servati et al. (2017), who note the importance of monitoring muscle movements, posture and body activity as they give great information about wellbeing and fitness level.

As the proposed applications do not all focus on the same target group nor intended use, some variety in monitored body signals was to be expected. In order to get to the final body signals, they need to be viewed with respect to the target group and intended goal, which is in our case keeping an eye on elderly patients, who tend to be physically inactive, which can lead to some specific complications. To summarize it can be said that for a system monitoring the rehabilitation of hip fracture patients, the most important facts to monitor are physical activity, heart rate (including heart rate variability) and respiration, whilst body temperature and blood pressure might also be viable, but not necessary for the given case.

2.3 – Sensors

After establishing the body signals most interesting to the given purpose, corresponding sensors need to be found. For this a number of articles proposing not only sensors that can be integrated into textiles but also ways of integrating them are being investigated.

When it comes to sensing the heart rate, the two most commonly used sensors are electrodes, which pick up the electrical signals causing the heart to contract, on the one hand, and optical sensors, which make use of the low light reflective properties of oxygenated hemoglobin, picking up changes in blood flow, on the other hand. Given the previously set required set of signals, the main issue with optical sensors is they cannot directly pick up the HRV, but instead need to estimate it using the pulse rate variability (PRV). Schäfer and Vagedes (2013) observed during a research, that, while the PRV can be a good estimation of the HRV with young and healthy subjects in rest, this correlation sometimes becomes not acceptable when the subject is under moderate physical or mental stress.

The ‘golden standard’ in medical applications are so called ‘wet’ electrodes, with which Nemati, Deen and Mondal (2012) point out several disadvantages. Firstly, they are inconvenient to the user, as the electrodes must be sticked to the body, requiring the spot to be cleaned and shaved beforehand. Moreover, can long-term exposures lead to skin irritations, allergies or even toxicological issues. They propose a ‘dry’ electrode, making use of a conductive metal part separated from the skin by a non-conductive material, such as fabric. This leads to an increased convenience for the user, but also makes the results more vulnerable to noise due to the high impedance. However, the general direction is noted as promising for future applications. Advancing the level of integration, Schwarz-Pfeiffer, Obermann, Weber and Ehrmann (2011) describe a process of creating a textile electrode by layering two conductive fabrics, held apart by non-conductive spacer thread, creating a textile ECG sensor of the second level of integration. It is stated that while there does exist some research with such elastic electrodes, in “many cases more stable and reliable ECG signals can be detected by non-elastic woven electrodes which are integrated in a knitted sensory shirt”. Another approach is being introduced by Quandt et al (2017) who make use of a specially melted soft polymer optical fibers to create a textile optical sensor. Again, the focus was on developing a convenient and comfortable medical heart rate sensor. They noted a problem with traditional electrodes, which is the development of pressure ulcers when it comes to long term monitoring. This was solved by fully integrating the electronics into the fabric, allowing for e.g. sweat to pass through, which is considered beneficial for ulcer prevention. The resulting sensor is a “low-friction, flexible, embroidered” one, enabling for an easier long-term monitoring of patients.

Second, the tracking of respiration is to be observed. According to Zeagler (2017), respiration is most often tracked making use of the expansion of the chest cavity. For this purpose, Schwarz-Pfeiffer et al (2011) mainly investigated the field of smart, knitted textiles and demonstrated some sensor possibilities in knitted textiles, which bring the advantage of high flexibility and therefore also higher comfort compared to traditional ones. Making use of either resistive properties, piezoelectric crystals or the properties of optical fibers, he proposed three kinds of respiration sensors that can seamlessly be integrated into knitted fabrics. However, they also reported that the elastic properties of knitted fabric often lead to less accurate sensor readings.

Being the easiest to track, activity is mostly being monitored by accelerometers. This is also part of the content of a study carried out by Aminian et al (1999), who used two accelerometers for gait analysis in hip patients to compare the gait cycles before and several months after surgery. The study found that accelerometers track activity and even gait cycles as good as the common practice of using pressure sensors at the feet. Furthermore, the study of Curone et al points out the possibility of integrating existing accelerometers into clothing due to their small size.

This paragraph of course only gave a small overview about the possible sensors and intends to proof the existence and development of the technology needed for development of a healthcare textile application. In a possible system, these sensors could easily be integrated and should be reliable, however other factors such as robustness and energy consumption need to be kept in mind.

2.4 – Body Placing

As smart textiles are meant to monitor body signals in a non-obtrusive way, the placing of the sensors is limited to the skin covered by a textile. Depending on the piece of clothing chosen, this can be little to much. However, not all body signals can be read everywhere on the body, heart rate readings for example require an artery for accurate readings. The following paragraphs will give an estimation of where the previously distilled body signals can be measured best.

As previously mentioned, two different heart rate sensors can be chosen from. Due to the nature of ECGs, Zeagler (2017) noted, that electrodes must be placed "on the chest, or arms depending on the preciseness of measurement needed". PPG sensors on the other hand are described to need veins or arteries close to the skin, which mostly occurs on extremities such as feet, around the hands and the head. However, as Jarchi and Casson (2016) mention, using a PPG on the lower half of the body results in significantly more motion artifacts interfering with the readings and gave them an average error of 9bpm, making it advisable to stay within the upper part of the body.

During their research, Schäfer and Vagedes (2013) also noted an increase in accuracy of the conversion between PRV and HRV when placing the sensor at a more central position such as the auditory canal, which might be important if the textile is applied to a position on the body, where ECG readings might become too noisy.

The respiration sensors proposed earlier by Schwarz-Pfeiffer et al (2011) all measure stress instead of actual air flow. This has also been noted by Zeagler (2017) as most other respiration sensors only measure chest cavity expansion rather than the air breathed as well. This limits the placing of such sensors of course to the upper torso. However, another approach is outlined by using thermistors placed inside the nostril, efficiently tracking breathing patterns.

Thirdly, body motion needs to be tracked. According to Zeagler (2017), the main location for tracking full body motion is upper torso, namely the chest or the upper back. Other locations, mainly the limbs, can be used to track this specific limbs motion, while the soles and bottom can also further be used to track the force of motion. This could be particularly interesting for the given application.

In another research, Hwang, Reh, Effenberg and Blume (2016) used one single, head worn accelerometer for gait analysis and proved this solution to work even better than their control unit consisting of a wrist-worn pedometer. This research suggests a gait analysis, but at least a step detection, should be possible anywhere on the center body, as the shocks from the steps get transferred through the whole body.

To conclude, different locations on the body bring different advantages and disadvantages, however, being able to track activity, respiration and heart rate, the chest proves to be the best fitted location of the body for the system. The development of a shirt would therefor advisable, as it covers the whole torso, giving a lot of space for electronics and systems and at the same time covering the most important body signal sensor locations.

III - Methods and Techniques

Creative Technology Design Process

The design process of this project follows the method proposed by Mader and Eggink (2014). In its core, the *Creative Technology Design Process* is a combination of two different concepts, the first one being the *Divergence and Convergence Model* and the second one being *Spiral Models*. *Divergence and Convergence* Models are aimed at giving as much space to creative thinking as possible. During these two phases its name is based on, first many ideas are generated, possibly with use of several brainstorm methods. This stimulates the designer to explore different options and perspectives. After this, the *converging* phase is used to narrow down the solution space by use of requirements and knowledge until a desired solution is reached. The other concept of models, *Spiral Models,* is rooted in the observation of design processes of professionals. In order to reach a design solution, few people use a strict order of steps rather than taking steps without a set, logical order. Still sticking to questions relevant to the original question and context, designer often encounter questions raising other questions that need to be explored first, while still generally following the process of problem understanding and definition, project planning, idea generation and evaluation. Together these two models form the *Creative Technology Design Process* as depicted in figure 1. As can be seen, multiple phases containing both follow each other. Each phase is a complete instance of both models, resulting in a complex but not strictly set process.

The *Ideation Phase*, the first of the three circular phases, is the starting point of the process. Usually there is an incentive of some sort that can origin from a client, a creative idea or from so called tinkering, which is the experimental use of technology. This incentive forms the starting point, from where different inspirational techniques are used in order to come up with a narrowed down project idea, which has been evaluated using a set of requirements that come from problem analysis.

In the next phase, the *Specification Phase*, the project idea from the previous phase is turned into prototypes which are evaluated and improved, (partially) merged into new prototypes or completely disregarded. Due to the volatile nature of this process, prototypes often only represent a small aspect of the final product and aim to only represent smaller aspects like the look, the feel or the functionality to test the experience. For this a technique called *Rapid Prototyping* is often used which is a name for quick prototyping using paper mock-ups, lasercutted parts, Arduinos and similar, quick and easy techniques.

After this, in the *Realization Phase*, the findings, ideas and specification from the previous phases are used together with engineering design methods to finalize the product. The end product then is evaluated with respect to the set specifications and requirements.

The final *Evaluation Phase* is used to evaluate the product and test the functional and non-functional requirements that had been set in earlier phases. In case of end-user products this is often done by use of user testing. Furthermore, the product is positioned in the existing market to identify future possibilities.

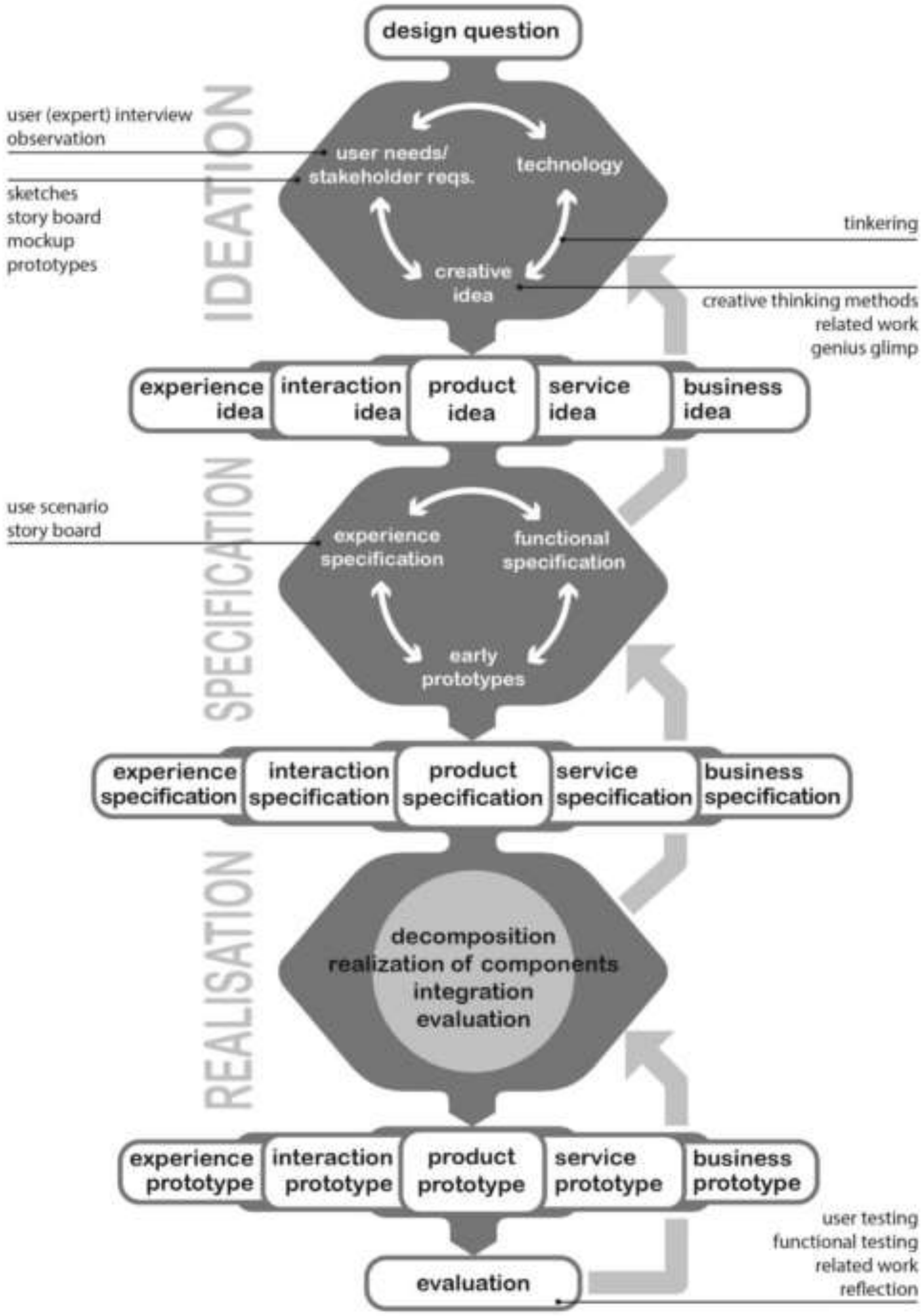

Figure 1: Creative Technology Design Process; Source [1]

Stakeholder Analysis

As with any project, it is of particular interest to identify possible stakeholders of an idea that is aimed to be turned into a product. These stakeholders are formed by the group of people that share any kind of interest with the project idea or final product. Therefore, they are not necessarily limited to the end-users, but may also include project supervisors and clients. After doing this, the gained knowledge can be used to research the particular interests the single stakeholders have in the product and to identify requirements these people may have for the end product. These requirements can be weighted according to the influence and interest stakeholders may have on the project.

Personas

Personas are a common tool used in project planning and the ideation phase. In case of a product that aims at a large group of people rather than some identifiable individuals, they are a tool to get a better feeling of stakeholders. Generally, while the person a persona is describing is fictional, the information included should be based on research and facts. Using this information, the theoretical person is created by giving him/her a background story, motivations and frustrations. This ensures an authentic user that could very well exist would be interested in the product.

MoSCoW

The MoSCoW method in project planning is a tool used for requirement organization not only limited to functional or non-functional requirements. The name comes from the different categories the requirements are sorted in: *Must have*, *should have*, *could have* and *won't have*. The way to sort is the following: *Must haves* are, as the name suggests, critical for the function of the product and need to be implemented to call the project a success. *Should haves* on the other hand, may be as important as some *must haves*, but are not as critical to the current state and can therefore be held back until a later state. Third, *could haves* are not important to the product but can improve user experience or function at little cost and may therefore be implemented if time and resources allow. The last group, *won't haves*, are generally neither important to the current product nor could be included in an efficient way. The advantage of the MoSCoW method however is that *won't haves* are rarely disregarded completely but rather stay in this group and are reconsidered with every product cycle.

PACT Analysis / Scenarios

A *Pact Analysis* is a tool to assess the current situation of the field where a new product aims to establish itself and can give insight in problems the product could solve. The name comes from the four sections that are being analyzed: *People* focuses on the stakeholders, and goes as far as identifying physicality, language, cultural background etc. In the *Activity* section, the nature of activities within the target field are analyzed. This includes goals, the types of actions but also aspects such as the regularity. The *Context* section continues to identify the circumstances the activities are done under. This includes, but is not limited to, the physical and the social environment. *Technology* then collects the technologies that are already being used for these activities in this context and the ones that may come up in the future.

Scenarios are generally used in product development to get a feeling for the situation of end-users within a given context. Sometimes already a part of a *PACT Analysis*, a story is told about an activity a potential user is conducting in the current situation, to then identify how the product in development can affect this process and justify the development.

Weighted Decision Matrix Method

The *Decision Matrix Method*, sometimes also called *Pugh method* after the inventor, is a method to qualitatively rank different options from a set, where the options are multidimensional and have a number of criteria which can be scored. All scores within one option are then added up and the options ranked accordingly. The difference between a weighted and a non-weighted decision matrix is that in the former, criteria can be of individual importance and are therefore not equal in weighting in the adding process.

User test

User tests are usually an important step in product development. Using various techniques, the product is being evaluated before being put into the market, to identify flaws and weaknesses to improve it. As explained earlier in the *Creative Technology Design Process*, user tests are generally conducted during each phase and can lead to reconsiderations and the current phase restarting. As mentioned, user tests can be conducted in a number of ways, while the ones used will be *Moderated Usability Testing* and the *System Usability Scale*.

In a *Moderated Usability Test*, the product is being tested on users while being in contact with a researcher. This brings the advantage of the testers being able to give unfiltered feedback, which has not been biased or filtered by their memory. Furthermore, it gives the researcher the chance to directly observe the behavior of the users, which can be an important source of information as well.

The *System Usability Scale* is a standardized questionnaire used to evaluate the usability of a system. It's focus lays on the user experience and consists of questions such as *"I thought the system was easy to use"* or *"I had to learn a lot before being able to use the system"*. These questions are being rated by the subject on a scale from one to five and then accumulated using the accompanied algorithm. The result is a value from 0 to 100 that is especially of value for comparing iterations of a product.

IV– Ideation

The following chapter will focus on the *Ideation Phase* of the *Creative Technology Design Process*. This first phase of the product development will be used to identify stakeholders of the project and based on this establish requirements of the healthcare system that is being developed. After this, related work in the health-tracking device field will be presented and based on this, novel ideas are being generated and collected. These ideas will then be put into a weighted decision matrix to come up with a novel product that meets the requirements.

Stakeholder Identification

The beginning of the ideation process requires the project's stakeholders to be identified. Here, one can distinguish between direct and indirect stakeholders, where the direct ones have direct impact on the project development, while indirect stakeholders are mostly concerned with the end product. Therefore, two direct and three indirect stakeholders have been identified and will be presented in the following.

The *Product Developer (O. Horst)* is the student developing the product. This stakeholder has the greatest impact on the final product, as all decisions are ultimately made by him. Due to the project being ultimately evaluated by the *Supervisor*, his main interest is meeting the requirements set by the *Supervisor*. Another interest involves the project meeting his particular set of skills and interests.

The client (BSS-Twente & ZGT), being represented by *M. Vollenbroek-Hutten*, is the second direct stakeholder. While also being affected by the end-product, they also have a high influence on the development process, as important design decisions are being run by the supervisor. The client already has own ideas about the final product, which need to be identified and discussed. The interests of this stakeholder are that these ideas are met and further that the product is usable in the given context.

Hip-Fracture Patients form the first large group of primary users. They only have little influence on the project and have to rely on their interests being identified and brought into play by the direct stakeholders. Interests of this group are driven by their desire for a good rehabilitation with the least amount of inconvenient and hindering factors possible.

Therapists watch over the patients and are the second indirectly affected stakeholder group. Due to their work with the patients and their responsibility for the rehabilitation process, their interests cover the medical side, as they want data about their patients that can help them guide the process.

Nurses are the last group of indirect stakeholders and are mostly secondary ones. Only limited interaction between them and the system takes place. However, due to the often stressful day of this user group their interests towards the project mostly involve their actions not requiring large amounts of work.

Personas

In the following section, the indirect stakeholders will be characterized by the use of personas. For this, available data and reasoning on the mean target population will be used.

Anke (Patient I)

Anke, who is 80 years old, widowed and is coming from Hengelo, lives in an apartment close to the center. She used to do a lot of sport and still keeps in shape by taking walks through the park and enjoying the sun and fresh air.

Occasionally one of her daughters is coming by for a visit and checks on her and lends a hand for the harder chores. They also gave her a smartphone to keep in touch and call them if she needed anything, but she rarely uses it. Other modern electronics like computers never really got to her.

A week ago, when she went for another walk, she fell on the stair and had quite some problems getting up, as she had a sharp pain in her left leg. When the ambulance arrived, they took her to the hospital as a hip fracture was diagnosed and required immediate surgery.

She got out of the hospital after three days and was moved to a rehabilitation center, where she does not have much to do. Once a day she has an appointment with a therapist, who is helping her to get back on her feet.

In the morning, after getting dressed, she eats breakfast in the dining room and chats with the other patients. In the afternoon, she mostly sits in the dining room for chats or card games with the others or goes to her room to watch TV.

Even though she desperately wants to return to her apartment, she is too afraid of walking without her therapist watching over her. Thus, takes her wheelchair if she goes somewhere. By her therapist she got some exercises she can do alone and if she remembers she usually does them but often gets scared. However, she wants to try walking with a walker soon to keep her muscles working.

Anna (Therapist)

Anna is a 37 years old woman from Enschede. She has already been married to her husband for six years now and they recently got a son, who turned one last month. After high school, she studied physiotherapy in Maastricht, but got back to Enschede after she met her now husband.

She always was a very social person and liked to talk and help people who were worse off than her, which is why she decided for the geriatric sector and her job in the rehabilitation center. Here she is able to get people back on their feet again!

Usually she sees all of her patients each day when they come by for their daily session. She always knew there are huge differences in the motivation of the different patients but tries to help everyone the best she can. At the end of each session, she always gives them a few exercises to do on their own but often suspects them to forget or just not do them. And even though she knows that it's their life and their decision, she would like to keep track of them to help and understand them better.

This is also important, as she needs to keep track and possibly adjust the goals of the rehabilitation, keeping them realistic but as high as possible. But as these differ from patient to patient, more information about their status would make her job easier.

Lisa (Nurse)

Lisa turned 27 last week. Her birthday she celebrated with her boyfriend and some friends at the lake near Enschede. On the weekend after her parents from Groningen came by and invited her to dinner, and as she rarely sees them, she was very happy about this gettogether. During the week her day is very full, as she has a lot to do due to her job in the rehabilitation center in Delden. Nevertheless, she is still happy with the job choice she made, and as she already had a lot of experience from taking care of her grandmother, she got used to the work quickly.

In the morning, she usually takes her round through her corridor, helping the patients to get washed and dressed if necessary. When the meals are ready, she also sometimes helps patients getting to the *restaurant and in the rest of the time she is busy taking care of the patients, cleaning up or doing administrative tasks, all in all a very busy day. Sometimes she notices patients being very inactive but is not sure how to motivate them to do more. However, when she gets into a chat, she often notices that they just forgot their exercises and reminds them.*

It is to note that the target users vary a lot. Especially the patient personas may only be seen as an example rather than a general guideline. While the age of hip patients is mostly high, and the sex is mostly female, personalities, motivations, origins and goals show huge variations. Furthermore, they might have age related handicaps and diseases such as Alzheimer or Delirium. The solution should therefore cover different traits or at least be not hindered by them.

PACT Analysis Current Situation

In the following, a PACT analysis of the current situation in a rehabilitation center will be looked at, with focus on the acquirement of body artifacts.

People:

- Therapists
    - Nationality: Dutch; Language: Dutch, (English); Age: 30-50;
    - Professionals in the medical sector, good cognitive abilities
    - Want the patients to rehabilitate well
- Patients
    - Nationality: Dutch; Language: Dutch; Age: >70; Sex: (mostly) female
    - Novice in the medical sector, below average cognitive abilities (Hartshorne and Germine (2015))
    - Want to rehabilitate well, least amount of inconveniences
- Nurses
    - Nationality: Dutch; Language: Dutch, English; Age: 25-40
    - Professionals in the medical sector, good cognitive abilities
    - Want to help the patients, do not want large increase in workload

Activities:

- Regular task: Measuring heartbeat
    - The patients skin needs to be prepared before the electrodes applied. The patient needs to stay hooked up for the duration of measurements
    - Less precise: Measurement by hand for a minute
- Non-existent task: Measure activity
    - Workaround: Asking about exercises

Context:

- Rehabilitation center; Friendly environment; Multiple floors, rooms, hallways, cafeterias and exercise room; Lots of people, mostly patients
- Nurses may help the patients getting ready in the morning and with other needs over the day
- Patients meet the therapist once a day for exercise

Technologies:

- Stationary ECG
- Connected work-out stations to record progress
- Computer to store and visualize data

Current Scenario

In the morning, Anke wakes up and when she tries to get up, she remembers why she is where she is: She had a hip fracture and is now, after the surgery, in a rehabilitation center and while she can sit upright, she is not able to get up to go to the bathroom alone. Instead, she presses the button on the remote next to her bed which will alert the nurses. After a minute, Lisa comes into the room and wishes her a good morning. With her help, Anke is able to get showered and dressed. When she is sitting in her wheelchair, Lisa grabs her wrist and holds it firmly for some time to measure her heartbeat as she knows. After a minute, Lisa releases Ankes hand and together they get to the dining room, where Anke is given some bread and spread.

Some of the other patients are already eating and she joins them at the table and eats her breakfast while chatting with the others. Later this day, she meets up with her physiotherapist, Bob. While he is guiding her through some exercises intended to help her get walking again, he asks her about her day. Did she tried to walk a bit already and was a bit more active? She is not really sure what to answer and says that she did not walk yet, but did her best to get a bit of activity. They continue with some exercises at the machines and afterwards Bob shows her, that she actually did a bit of progress on the leg extension machine. After this, he finishes the session by asking her to try to stand up on her own some times later that day.

When the session ended, Lisa was already there to bring Anke back into her room, where she solves some Sudokus until it is dinner time and she meets up with the other patients in the dining room again. After they finish their meal, Anke stays a bit longer with the others but soon get tired and is helped to bed by the night shift nurse, who helps her getting changed.

MoSCoW

Using the MoSCoW method, the information gained via the stakeholder analysis, the personas and the PACT analysis can be used to extract requirements of the system in question. They will be divided over the different categories of *functional and non-functional* requirements. In requirement creation, functional requirements specify what a system should do, while non-functional ones tell us how the system should work. As for example reliability is a typical non-functional requirement, some functional requirements will have non-functional fit criteria. The classification within the MoSCoW classes will be done with respect to the interests of the stakeholders.

Requirement #1	**Requirement type:** Functional
Value:	**Attribute:** Heart rate measurement
Description: The system should be able to accurately measure heart rate.	
Rationale: The heart rate is a great indicator of body exercise and wellbeing and was requested by the client.	
Source: Servati, Zou, Wang, Ko and Servati (2017)	
Fit criteria **Usability testing:** The system can be tested using a Ag/AgCl Electrode system as a comparison measure. Above an accuracy of 99% the system can be seen as accurate enough.	
Priority: Must have	**Conflicts:** Easy usability and non-obtrusiveness require use of less accurate measurement methods.
History: Created 22-04-2018	

Requirement #2	**Requirement type:** Functional
Value:	**Attribute:** Heart rate variability measurement
Description: The system should be able to accurately measure or estimate heart rate variability.	
Rationale: As seen in the literature, heart rate variability is a great indicator of physical and mental condition and can hint towards illnesses.	
Source: Servati, Zou, Wang, Ko and Servati (2017)	
Fit criteria **Usability testing:** The system can be tested using an Ag/AgCl Electrode system as a comparison measure. Above an accuracy of 95% the system can be seen as accurate enough.	
Priority: Must have	**Conflicts:** Easy usability and non-obtrusiveness require use of less accurate measurement methods. Optical sensors can only estimate.
History: Created 22-04-2018 Adapted Rationale -16-07-2018	

Requirement #3	**Requirement type:** Functional
Value:	**Attribute:** Activity measurement
Description: The system should be able to accurately measure steps taken.	
Rationale: Activity is very important to hip patients in order to get as closely as possible back to the previous state. Furthermore, inactivity can lead to avoidable complications.	
Source: Panula et al (2011), Obrant (1996)	
Fit criteria **Usability testing:** The system can be tested using a number of pre-defined tests with a number of steps. It should be aimed for a 95% accuracy, but everything above 90% should be usable for distinguishing activity levels.	
Priority: Must have	**Conflicts:** None
History: Created 22-04-2018 Lowered fit criteria 25-06-2018 (Reasons explained in Algorithm chapter)	

Requirement #4	**Requirement type:** Functional
Value:	**Attribute:** Posture measurement
Description: The system should be able to determine body posture.	
Rationale: Activity is very important to hip patients in order to get as closely as possible back to the previous state. This means also that it can be good to determine posture: Sitting, standing, laying and walking	
Source:	
Fit criteria **Usability testing:** The system can be tested using a number of pre-defined tests in different postures. A 95% accuracy should be aimed for.	
Priority: Should have	**Conflicts:** None
History: Created 22-04-2018	

Requirement #5	**Requirement type:** Functional
Value:	**Attribute:** Battery life
Description: The system should be able to run on rechargeable battery and last long enough	
Rationale: Battery failure can hinder continuous monitoring and need to replace it creates an obtrusiveness.	
Source: Servati, Zou, Wang, Ko and Servati (2017)	
Fit criteria **Usability testing:** The system can be tested for battery life. It should at the very least last one full day. Better would be 3-5 days.	
Priority: Must have	**Conflicts:** The size should be kept to a minimum
History: Created 22-04-2018	

Requirement #6	**Requirement type:** Functional
Value:	**Attribute:** Respiration measurement
Description: The system may be able to monitor respiration.	
Rationale: Respiration patterns can hint wellbeing, activity level and even a number of diseases.	
Source: Servati, Zou, Wang, Ko and Servati (2017)	
Fit criteria **Usability testing:** The system can be tested using a number of pre-defined tests with a number of breaths taken. Depending on the intended use an accuracy of 95% to 99% may be needed.	
Priority: Won't have	**Conflicts:** Respiration can only be accurately measured on the chest or in the mouth/nose
History: Created 22-04-2018 Lowered Priority 18-06-2018	

Requirement #7	**Requirement type:** Functional
Value:	**Attribute:** Balance measurement
Description: The system could be able to track the pressure put on each foot	
Rationale: Fear of using the injured leg might lead to imbalance. Furthermore, sometimes the patients need to go easy on the injured leg.	
Source:	
Fit criteria **Usability testing:** The system can be tested using a scale. An accuracy of 90-95% would serve the purpose well enough	
Priority: Could have	**Conflicts:** Actual weight bearing is only measurable at the feet
History: Created 22-04-2018	

Requirement #8	**Requirement type:** Non-functional – Accessibility
Value:	**Attribute:** Data retrieval
Description: The system needs to store data in an easily retrievable way.	
Rationale: While giving valuable information to the therapist, the system should not add too much more work to the process as one of the objectives is to lower the workload of caretakers.	
Source:	
Fit criteria **Usability testing:** The data retrieval can be tested and should take a previously instructed user not more than 2 minutes.	
Priority: Must have	**Conflicts:** None
History: Created 22-04-2018	

Requirement #9	**Requirement type:** Non-functional – Usability
Value:	**Attribute:** Adaptability
Description: The system needs to easily be implemented in the users clothing	
Rationale: Most patients wear and wash their own clothing. Therefore, it needs to be easily put in place and taken off.	
Source: Observations	
Fit criteria **Acceptance testing:** Users can be asked to put the system in place and should not fail in doing so.	
Priority: Must have	**Conflicts:** The system needs to be integrated and be on the right spot for the sensors to work.
History: Created 22-04-2018	

Requirement #10	**Requirement type:** Non-functional – Aesthetics
Value:	**Attribute:** Acceptance
Description: The system needs to be aesthetically non-obtrusive	
Rationale: If a system is found aesthetically disturbing, users do not like putting it on, resulting in less willingness to participate	
Source: Observations	
Fit criteria **Acceptance testing:** Users can be asked to rate the aesthetical appearance and can be asked if they would wear it if it is good for them. An acceptance of 90-95% should be achieved.	
Priority: Must have	**Conflicts:** The electronics might need more space and make the system a bit bulky
History: Created 22-04-2018	

Requirement #11	**Requirement type:** Non-functional – Usability
Value:	**Attribute:** Robustness
Description: The system needs to be robust enough to withstand daily interaction. If it is integrated in clothing and parts need to stay inside, they need to withstand a washing cycle.	
Rationale: The system will be in daily use and should not get inaccurate or broken by it.	
Source:	
Fit criteria **Usability testing:** The system can be used under extreme circumstances and should not give inaccurate/no results.	
Priority: Must have	**Conflicts:** The electronics might need more space and make the system a bit bulky
History: Created 22-04-2018	

Requirement #12	**Requirement type:** Non-functional – Aesthetics
Value:	**Attribute:** Appropriateness
Description: The system needs to be appropriate to wear both inside and outside	
Rationale: If a system is found inappropriate to wear in a given context, users do not like putting it on, and are more likely to take it off resulting in less functional ability of the system	
Source: Observations	
Fit criteria **Acceptance testing:** Users can be asked to rate the appropriateness of the system and can be asked if they would wear in a number of contexts. An acceptance of 95% should be achieved.	
Priority: Must have	**Conflicts:**
History: Created 18-06-2018	

Requirement #13	**Requirement type:** Non-functional - Usability
Value:	**Attribute:** Comfortableness
Description: The system needs to be comfortable to wear for the user	
Rationale: If the system is uncomfortable to wear, users tend to take it off more easily or even not be willing to wear it at all.	
Source: Observations	
Fit criteria **Acceptance testing:** Users can be asked to rate the comfortableness on a scale from 1-10. Furthermore, they can say whether they could see themselves wearing the system on long term. Yes/No. A comfort level of at least 6 should be reached together with an long-term acceptance of >90%	
Priority: Must have	**Conflicts:**
History: Created 19-06-2018	

Related work

After having established users and requirements, the most important aspects of the final solution are set, a look at the state of the art of (medical) fitness trackers and monitoring devices is to be taken. For this not only commercially available solutions will be considered, but also recent research projects will be shown. The main criteria for this search will be the monitoring of heart rate and/or activity and non-obtrusiveness. After the findings are presented they will be compared with each other using the previously set requirements to find issues and strengths. This will be used later in the ideation phase to get to a concept that uses the found strengths and betters the weaknesses. Within monitoring devices there are huge differences not only in what they track but in where the sensors are integrated as well. From the probably best-known ones, wrist worn trackers, over chest worn implementations to less obvious ones at the feet or head. The found examples will be presented in the above-mentioned order, grouping them in clusters.

Wrist worn trackers

Wrist worn trackers are most commonly used nowadays, as already most smartwatches have a step counter build it, but there are trackers that serve the sole tracking purpose better. However, most work and track pretty similar, which is why only one example will be given as an impression.

Fitbit Alta HR

Fitbit offers a wide range of devices related to sports, the Alta HR is only an example but is fit the best out of the wrist worn trackers offered. It can be connected to an app to wirelessly transfer the collected data. The most interesting sensors include an optical heart rate sensor and an accelerometer for activity tracking. Furthermore, it offers sleep analysis and notifications and can act as a watch and a calendar, but these functions are less interesting for the given application.

Figure 2: Fitbit Alta HR; Source [2]

The main advantage of the Alta HR is the easy use, as it only needs to be put on the wrist like a watch and starts tracking. The battery lasts for up to seven days, which is another huge advantage. Also, the device can store detailed minute-to-minute data for up to seven days as well. The fourth advantage is the robustness, as it is shock- and water-proof.

On the negative side is first the use of an optical heart rate sensor. As these can only measure the pulse, HRV can only be estimated and is prone to errors. Also, as Fitbit does not track HRV on its own, it would need to be hacked, in order to get data. If this is even practical, it would possibly also affect battery life negatively as well. Furthermore, a general problem of wrist worn trackers is false flagging when using walking aids. Movement in a wheelchair often gets picked up as steps due to the movement of the arms, while walking with a walker keeps the hands still, resulting in no steps being picked up.

Chest worn trackers

Most commonly used professional devices are placed on the chest, as, as discussed earlier, it is the best place to get accurate ECG measurements. Here a lot has happened within the last years. While some trackers still are traditional modules, some devices make use of smart textiles.

VitalPatch

The VitalPatch is a medical grade application delivering a variety of sensor data, the most important for the given case being heart rate, heart rate variability and activity. But also other sensor data can be useful, as it furthermore tracks respiration rate, posture, skin temperature and fall detection.

Figure 3: VitalPatch; Source [3]

The advantages here are medical grade accuracy and a variety of sensor data, all being tracked in one spot. Furthermore, a battery life of four days allows for long term monitoring. Also, wireless communication enables an easy data retrieval to a computer.

On the contrary, said battery is non-rechargeable and therefore needs to be replaced, and while this allows for quick re-deployment, it is not practical on a large scale. Furthermore, the patch needs to be put in place by a caretaker and the skin needs preparation due to the use of wet electrodes. These also give the danger of harming the patients skin during the monitoring or when taking it off.

Wealthy Project

The Wealthy (*Wearable Health Care System*) project is a collaborative research funded by the EU, aimed at creating a smart shirt with integrated sensors to monitor cardiac patients in the rehabilitation phase. During the development, textile sensors have been created measuring heart rate via an ECG and respiration rate.

Figure 4: Wealthy Project; Source [4]

The main advantages of the system are obvious, including the sensors in the textile, do discomfort at all is created for the wearer. Furthermore, it can be easily put on just as a normal shirt, allowing for easy deployment and data can be wirelessly transferred to a computer.

On the negative side, activity is not being tracked by it. Additionally, the shirt itself basically is the sensor, which would require the user to always wear the shirt given by the rehabilitation center. For the rehabilitation center this would require buying at least two sets of shirts per patient. Lastly, the bulky main component of the shirt may bother some patients.

Hexoskin Smart Shirt

The Hexoskin smart shirt practically is an improved, commercial version of the above-mentioned ‘Wealthy’. It comes with textile sensors measuring heart rate and HRV using an ECG, respiration rate and activity.

Figure 5: Hexoskin Smart Shirt; Source [5]

Main advantage is the accurate measurement of all needed bio-signals, but as with the ‘Wealthy’, the shirt allows for a completely non-obtrusive and easy-to-use measurement technique. Depending on the use the battery can last up to 30 hours and up to 600 hours of data can be stored. Furthermore, raw data can be exported, or existing programs can be used. Data can be wirelessly transmitted using Bluetooth and the shirt is washing machine safe.

The main disadvantage again is the use of a shirt as a sensor, as it needs to be washed and replaced, therefore requiring (at least) two sets per patient. Also, patients might prefer to wear own clothing.

Ambiotex Shirt

The Ambiotex shirt is another shirt that includes sensors in a sports-shirt, giving an accurate heart rate and HRV measurement. The main unit functions as a communicator, battery and processing unit. This shirt is tailored even more to sports than the others.

Figure 6: Ambiotex Shirt; Source [6]

Similar to the previously mentioned shirts, the Ambiotex shirt allows for a comfortable way of monitoring. Also, the battery lasts for 24 hours of continuous monitoring which is considered enough. The same amount of data is also stored locally and can always be retrieved using a Bluetooth device. Another well thought advantage of this implementation is the easily attachable main unit, which clips on using magnets, meaning an easy removal before washing it.

On the other hand, the magnetic attachment might interfer with other clothing worn over it. Furthermore, the limited signals being monitored make it unpractical for the given purpose.

Head worn trackers

Head worn trackers are less common, probably due to the fact that not much is normally worn on the head. However, there are a couple of solutions that are placed around the head, some of which will be portrayed in the following.

Wireless Heart Monitor

During a research, Da He, Winokur and Sodini developed a "A continuous, wearable, and wireless heart monitor using head ballistocardiogram (BCG) and head electrocardiogram (ECG)", which is placed next to the ear and measures heart rate (and HRV) using two different techniques, one of which could additionally be used to track activity.

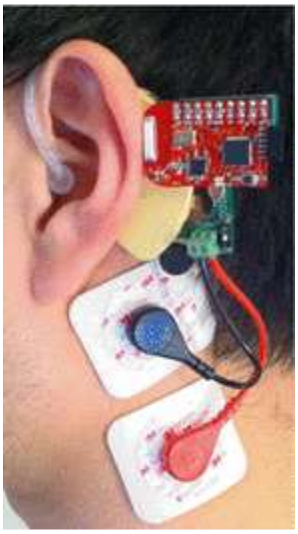

Figure 7: Wireless Heart Monitor Prototype; Source [7]

The advantage of the mentioned system is the accuracy of it due to the two-lead approach. Furthermore, the system is supposedly rather non-obtrusive to people used to pressure around the ears due to glasses and sends the raw data wirelessly to a computer, but on-board processing could be adapted to pre-set cases.

The main disadvantages arise due to the project being only a prototype, therefore the robustness is more then questionable. Besides, battery life is fairly short and in it's current state no on-boar storage is implemented. Lastly the use of wet electrodes gives the mentioned negative effects of the need for assisted putting on and complications with long-term monitoring and taking it off.

Instabeat

The Instabeat is a Lebanese start-up aimed at activity tracking for professional swimmers. The tracker is worn under the swimming goggles (as seen in figure 7) and monitors heart beat and swimming activity tracking. Life data is being wirelessly transferred and displayed in the swimming goggles at the same time. As the product is still in development, some information such as battery life could not be found.

Figure 8: Instabeat; Source [8]

The advantage of such a system again is the adaptability, it just needs to be put on and works. Furthermore, most of the necessary data can be tracked using the sensors provided. It has been rated as very comfortable to wear, as it is worn under glasses (or swimming goggles), where one is used to pressure.

The main negative points are the bulkiness of the product, which is due to the requirement of water-proofness and the included feedback system, and the use of an optical heart rate sensor, making HRV hard to retrieve.

Lifebeam Hat

The Lifebeam Hat is a product by the company Lifebeam, which has been developed after a series of Airforce helmets and uses the technology to create a lightweight, head-worn heart rate monitor.

Figure 9: Lifebeam Hat; Source [9]

The system is very easy to use and has been rated as comfortable as usual hats, making it very non-obtrusive. The battery life is 17 hours of continuous use, which is enough for one full day of tracking. Additionally, using the heart rate sensor, the hat can calculate cadence and calories burnt, which may also be a way of tracking activity, and according to online sources, the sensor may also be usable for activity profile analysis. All data can be transferred wirelessly using Bluetooth.

The main issue as mentioned is that the hat does not include an accelerometer for activity tracking, but another issue is that hats are normally not worn inside, making the it a less-perfect ‘carrier’ of the sensors.

Vi Headphones

The Vi headphones are the most resent product by Lifebeam. They are being advertised as an AI sports coach and deliver next to normal headphone aspects heart rate, motion and elevation sensors. Apart from that an AI sports coach gives feedback to the user.

Figure 10: Vi headphones; Source [10]

The advantages of the system are accurate measurements (The same aerospace-grade sensors as in the hat are used) and the comfortable way of measurements, as the sensors are integrated into ‘usual’ headphones. Also, the data is transferred wirelessly to a phone. Lastly, as earlier discussed, in ear pulse rate variability measurements also tend to be more easily translated into HRV.

On the other side, the battery life is quite low (4-8h), possibly due to several power consuming functionalities such as playing music. Furthermore, a phone is needed, and the system cannot work without.

Foot worn trackers

Foot worn trackers, even though being quite uncommon, haven gotten some attention in the sports sector within the last years, as the foot it arguably the best spot for accurate activity measurement. In this section, two examples will be shown.

Sensoria Sock

The Sensoria sock combines textile pressure sensors integrated into the sock with a magnetically connected main module with an accelerometer, which is worn above the shoe. It is mostly aimed at runners but can be used to identify injury-prone running styles.

Due to the integration of sensors into a commonly used piece of clothing, the obtrusiveness is virtually non-existent while giving a very easy deployment. Furthermore, it can be used for accurate gait analysis and therefore be quite valuable for the therapist, as faulty walking habits can be identified early on. The sock itself is washable and the module sends the data wirelessly to a smartphone.

Figure 11: Sensoria Sock; Source [11]

Negative points due to the previously set requirements are battery life and sensors. Probably due to the number of individual sensors, the battery lasts for only about six hours of usage. At the same time, heart rate is not measured and is also hard to measure on the foot. Furthermore, a phone is required for the use and the same problem of usability as with every other textile system mentioned applies.

Digitsole

The Digitsole aims at the same target group as the Sensoria sock and aims at delivering detailed gait analysis to the user by use of an array of sensors worn within the shoe below the foot.

Again, the deployment is fairly easy, as it only needs to be cut in the right size and be placed into the shoe. At the same time, obtrusiveness is kept at a minimum. It also delivers detailed information about the gait, enabling to discover issues early on. The battery lasts for up to seven days and data is sent wirelessly to a phone.

Just as with the socks, the system fails to monitor bio-signals, making it not usable for the given purpose. Furthermore, continuous Bluetooth connection to a smartphone is needed for operation.

Figure 12: Digitsole; Source [12]

Clip on tracker

The last group of trackers being discussed here are clip-on trackers. These can eaily be clipped on a piece of clothing and are therefore fairly common, despite their limited functionalities. In the following one example will be shown to get a general idea.

Fitbit Zip

Another tracker by Fitbit is the Fitbit Zip. It is much more simplified than the previously mentioned Alta HR and only consists of an accelerometer for activity tracking and a feedback screen. It is an example from the section of clip-on trackers, that can virtually be attached anywhere, but mostly on the belt or bra.

The advantages of this tracker are a long-lasting battery life of four to six months, making it perfect for long-term monitoring. Furthermore, the collected data can not only be stored in detail for up to seven days but also wirelessly transferred to a computer over the internet. Therefore, the tracker could be given out and would only be taken again when the patient is leaving.

Figure 13: Fitbit Zip; Source [13]

On the other hand, the main issue is that the tracker does not monitor any bio-signals and therefore fails to meet some essential requirements. Also, the batteries are non-rechargeable, which means they have to be replaced instead of charged when they run out.

Comparison of trackers

In the following, the portrayed trackers will be compared to each other with respect to the set requirements using a weighted decision matrix. For this they will be rated on a scale from 1 to 5 (5 being the best) for each of the requirements. Most of the times the non-existence of a feature will be indicated by a 1 and the existence by a 5. In between can either indicate the existence of possible issues with the feature or the possibility of implementing such a feature given the sensors the system offers. The systems' ratings will then be accumulated using a weighted algorithm.

#	1M	2M	3M	4S	5M	6W	7C	8M	9 M	10 M	11 M	12 M	13 M	Tot.
Alta HR	4	1	3	1	5	1	1	4	5	4	5	5	4	41,6
VitalPatch	5	5	5	5	5	5	3	4	4	4	5	4	5	53
Wealthy	5	4	1	1	n.a.	5	1	5	2	4	4	5	5	38,8
Hexoskin	5	5	5	5	4	5	3	5	2	4	4	5	5	51
Ambiotex	5	5	2	1	4	1	1	4	1	3	4	4	5	39,4
Wireless Heart Monitor	4	4	4	3	n.a.	2	3	4	4	4	2	3	3	36,5
Instabeat	4	2	4	3	n.a.	2	3	4	4	4	5	1	3	32,5
Lifebeam Hat	4	2	2	1	3	1	1	3	4	5	5	3	4	36,6
Vi	4	3	5	1	2	1	2	3	5	5	5	5	4	43,1
Sensoria	1	1	5	2	2	1	5	3	3	4	4	5	5	37,4
Digitsole	1	1	5	2	5	1	5	3	5	5	4	4	5	42,4
Zip	1	1	5	1	5	1	1	4	5	4	5	4	5	40,6

The comparison shows the strong points of chest worn trackers. The two strongest players are the VitalPatch and the Hexoskin shirt. Foot worn trackers in the other hand show weaknesses in the heart rate detection, which was expected due to the literature findings, as too many motion artifacts are present. The possibility of head worn trackers are illustrated by Instabeat and Vi but have some tradeoffs and weaknesses as well.

Generated Ideas

After analyzing the existing market, a head worn tracker was found to be most novel and achievable at the same time. Thus, the question "*How could a head worn health tracking device be implemented in the hip-fracture rehabilitation process*" will be focused on.

A brainstorm has been conducted on the accessories usually worn in the head region, in which technology could potentially be integrated. Limiting factors here were the size of the electronics and direct skin contact with some amount of pressure, which is needed for accurate heart readings in any case. Generally, the same sensors would be used for every idea, as they have proved to be the most reliable ones. Heart rate would therefore either be measured by dry electrodes or an optical sensor and for posture and activity an accelerometer is used. Other methods of heart rate sensing such as head movement have been found too unreliable, especially for heart rate variability sensing.

Figure 14: Head sketch

Figure 14 shows the general head sketch, that has been taken as a build-up for most of the sketches illustrating the generated ideas. In yellow, the arteries on the side of the head are shown, which are important to be present for optical heart rate sensing via PPG.

Hat

Figure 15 shows a cap, which would be similar to the LifeBeam Hat, with a difference in the sensors used. The shape obviously allows for a good amount of space for electronics and battery. Furthermorem the majority of weight would be centered and therefore comfortable to wear. Another plus is good access to the forehead, which usually has little hair, allowing for good and accurate measurment. A variation of this could be any other hat-type accesory. The downside of this is of course the same as with the LifeBeam Hat as well, that hats are usually not worn inside.

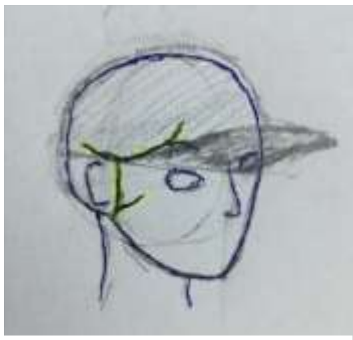

Figure 15: Smart Cap

Headband

The headband, as depicted in figure 16, is another variation of the hat idea. It brings the same advantages but tries to tackle the downside of wearing the system inside. Especially for women this could be an accessory wearable inside, as headbands can be better used as a fashion accessory than hats. Online research shows some variety on headbands that could potentially be worn inside as well. Furthermore, as most of the expected end-users are women, a fashion direction might be a good idea.

Figure 16: Smart Headband

Collar

Figure 17: Smart Collar

The smart collar (figure 17) would take another turn to the accessory use. Collars can be worn inside without any inconveniences and even be turned into a fashion piece as well. Again, this would probably be more interesting for female users. Furthermore, the arteries around the neck are quite close to the heart and transport large amounts of blood and are therefore perfectly suitable for optical heart rate sensing. In theory, the collar could either be made from fabric or even as a kind of necklace, allowing for quite some amount of customization.

Hearing Aid

Figure 18: Smart Hearing Aid

As elderly people often have hearing problems, hearing aids are a common accessory that is worn over the day and could be perfect for integrating a healthcare monitoring device like presented in figure 18, as there are already technology and batteries build in. Another advantage is that according to research, the relationship between heart rate variability and pulse rate variability increases if measured closer to the core of the body (inside of the ear). One downside however is that it could be hard to integrate the system into existing hearing aids as people will bring with them. Another downside would be the asymmetrical spread of the weight, which could cause an inconvenience. However, users normally are also used to this already.

Glasses

Figure 19: Smart Glasses

95% of the people over 75 in the Netherlands have to use vision aids, most of them use glasses. Integrating the system into glasses gives the benefit of a widely spread accessory, in which the system could easily be implemented or clipped on and look like shown in figure 19. Users usually are already used to pressure around the ears, which means the sensors would create only minimal inconvenience. As with the hearing aid, the asymmetrical spread of weight might be a problem.

Decision Matrix

In the following, a weighted decision matrix will be created based on the requirements set during the ideation phase and the researchers personal preference (14), opinion on novelty (15) and feasibility within the given time and resources (16). Functional requirements, where all options score the same due to the possibility of fulfilling the requirement are being ruled out. Again, the scores are accumulated using a weighted algorithm, where 14, 15 and 16 are of the same weight as *Must have* requirements.

#	1M	2M	5M	7C	9M	10M	11M	12M	13M	14	15	16	Tot.
Hat	5	4	5	4	5	3	4	2	4	1	2	5	42,4
Headband	5	4	5	4	5	4	4	3	4	2	3	5	46,4
Collar	5	5	4	4	3	4	5	5	3	2	3	3	44,4
Hearing Aid	5	5	3	3	4	3	4	5	4	4	5	4	47,2
Glasses	5	4	3	3	5	4	4	5	5	5	4	4	49,8

Using the matrix, the Smart Glasses idea is chosen for further development in the specification phase, also due to the fact that it is the most interesting to the researcher while still being estimated as rather novel and feasible to make. The hearing aid idea, which is following closely might be worth further research as well in the future.

PACT Analysis Possible Future Situation

The following section will use the previous PACT analysis and will look at the possible impact the proposed system might have on the current situation. To do this, changes in the previous scheme will be pointed out and a possible use scenario is presented. Some details related to the final product are still not fixed so some activities may have different options of doing them.

Activities:

- Applying/Maintaining the system
    - The silicon sleeve needs to be slid on the temple of any kind of glasses (and fixed in the right spot?)
    - The battery needs to be charged regularly
        - Inductive charging? Glasses are stored in a special spectacle case overnight / Placed on a special spot or device
        - Battery switching? Once in a while a component can be switched out by a nurse and the old one can be charged
        - Sensor switching? Once in a while the sensor needs to be replaced by a charged one which needs to be synced to the patient and the old one needs to be put on a charging station
- Measuring heartbeat
    - The system is automatically measuring the heartrate and heart rate variability while the glasses are worn and stores it on an accessible server
- Measure activity
    - The system is automatically measuring the steps taken while the glasses are worn and stores it on an accessible server

Technologies:

- Smart Glasses system
- Connected work-out stations to record progress
- Computer to store and visualize data

Possible Scenario

Anke wakes up and at first does not recognize the bed she is in, but quickly remembers her hip fracture and the rehabilitation center she moved to a few days back. She tries to sit upright, which works, but wants to call for a nurse to help her getting up and ready using the remote next to her bed. She reaches out for her glasses, finds them on her nightstand in a case and puts them on. On the right side, just next to the earpiece she recognizes the device that got mounted on the temple when she arrived here. She is not sure how it works, but it is supposed to monitor her stress and recovery process and gladly accepted it when she was told it could help her therapist to improve the care. Shortly after, Lisa walks into the room they wish each other a good morning. Lisa helps her to get up, washed and dressed and soon Anke is ready to get her breakfast. She sits down in her wheelchair and lets Lisa roll her to the dining room, where she sits at a table with some other patients she got to know over the last few days.

Later it is time for her daily physiotherapy session, for which she meets up with Bob. He greets her and together they do a few exercises. After a while, he tells her that he noticed that she was quite inactive since she got up and suggests joining some of the other patients for a stroll outside tomorrow. Besides this he also gives her a few exercises she can do on her own later. Bob is a bit worried about Anke, as she does seem a bit afraid of taking steps on her own, but the data he looks at after the session look promising as no complication occurred and her HRV value is high enough to show him that her body is doing fine, so he is confident she will be able to walk again soon. Later that day he even gets an update that she indeed was a bit more active during the evening, indicating that she followed his advice of exercising her legs a bit.

After she did some of the exercises Bob suggested to her, Anke gets ready for bed with some help of the night shift nurse. She feels a bit exhausted from the day and the exercises but feels good nonetheless as she feels that she did good to her body. She puts the glasses back in the case on her nightstand and quickly falls asleep.

Conclusion

Using stakeholder analysis, personas of the end users and a PACT analysis, requirements the final system needs to meet have been established and classified using the MoSCoW method. After this, research on the commercially available products and pre-existing research-projects has been conducted. As a market gap has been identified in the section of head-worn trackers, the generation of ideas focused on this field. The resulting ideas have then been evaluated using the requirements and three extra criteria, where the smart glasses idea has scored the best. It will therefore be advanced to the specification phase. However, the hearing aid idea will not yet be fully disregarded as it poses a great alternative, especially if a cooperation with a hearing-aid company could be achieved. The impact of the system was visualized at the example of a scenario and shows potential of the system as it can reduce the work of caretakers and at the same time increase the qualitative and quantitative data accessible to them.

V – Specification

Advancing on the previously selected idea, the following section will elaborate on the specification process from the general idea to a functional prototype. First it is necessary to look at the two different possible options to monitor the heartbeat, compare them and decide for one. After this, the functionalities and overall design will be specified further and a scenario and flow diagram will be created to get a feel for the product.

Heartbeat Detection

When acquiring the heartbeat of an individual, frequencies play an important role. While the average person's heartbeat at rest mostly ranges between 1 and 1.3Hz, sampling is needed at a higher frequency. According to the Nyquist–Shannon sampling theorem, when sampling a signal with the highest frequency f_x, a sample frequency of at least $f_{sample} = 2*f_x$ should be chosen. This is supported by Hejjel and Kellenyi (2005), according to whom a measured signal ranging from 0.5 to 20Hz proved sufficient for heart rate variability analysis.

Second, as mentioned in the literature findings, the two main options to measure heartbeat are electrical sensing and optical sensing. For the system which needs to be designed, it is advisable to choose one of these options early on, as they differ quite a lot in functionality and what needs to be done to extract information. The following paragraphs will therefore give a small overview on how each option works, elaborate on the tests which had been conducted and, in the end, decide for one of the options to work with.

ECG

The acquisition of heart signals via electrical sensing is performed by an *ECG*, short for *electrocardiogram*, device. These devices use the fact that the heart, as it is a strong muscle, needs an electric signal to contract. These signals travel through the heart and are measurable even on the skin. After filtering out unwanted noise, the signal has a unique shape as depicted in figure 20. As it can be seen, a heartbeat has five distinguishable points (P, Q, R, S & T), the most important ones for heart rate analysis being Q, R and S. Especially the R point can be of use for heart rate variability acquisition.

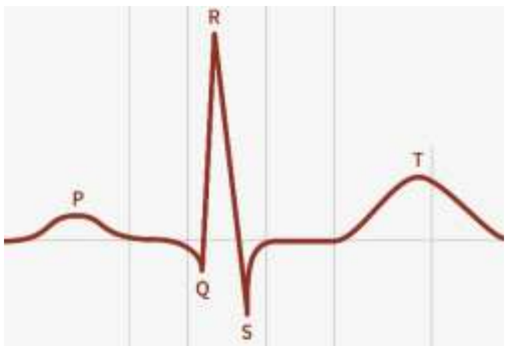

Figure 20: Example ECG signal; Source [14]

Usually an ECG is performed via a number of adhesive electrodes, that are being stuck to the previously prepared skin (shaved and cleaned). 'Gold standard' is the use of twelve leads spread out over the body to get the best signal. However, a signal has been proven to be already analyzable with the use of only three electrodes, one being a reference electrode for filtering purposes, which can sometimes be left out. Currently, wet Ag/AgCl electrodes are widely used for measuring for their great performance. Other electrodes mostly require some gel to be applied in between the electrode and the skin to increase the conductivity. However, there are also dry, or rather semi-dry electrodes being developed, which sometimes work dry, but mostly use the sweat that collects under the electrode as a conductive layer. Filtering of the signal acquired by an ECG happens with the use of hardware components, namely operational amplifiers, capacitors and resistors. Circuits build need to use precisely valued components to achieve proper filtering.

The main problems with this technique are the low voltages that can be picked up on the skin, which can easily be covered by noise. Especially 50 Hz noise, which gets radiated from any power outlet or device connected to one. Furthermore, motion artifacts from other muscles are picked up as well and can cover the desired heart signal as well.

During the research, a promising dry electrode proposed by Pourahmad and Mahnam (2016) has been found. A brass plate has been covered in gold and was put together with an amplifier and a filter. In their research, Pourahmad and Mahnam found the electrode to work significantly better than traditional gold-cup electrodes. This electrode has been tried to be rebuild during the research using the same materials but using amplifiers and filters only on a breadboard. In figure 21 both electrodes can be seen, the model from the paper and the recreated one. These electrodes then have been hooked up to a circuit shown in figure 22. Present in this circuit is first an amplification phase with a factor of 500, followed by a 4th order Sullen-Key Low-pass filter with a cut-off frequency of 50Hz. In theory, this circuit should filter out high-frequency noise and amplify an ECG signal from 1mV to 0.5V.

Figure 21: Proposed electrode model on the left, remade electrode on the right

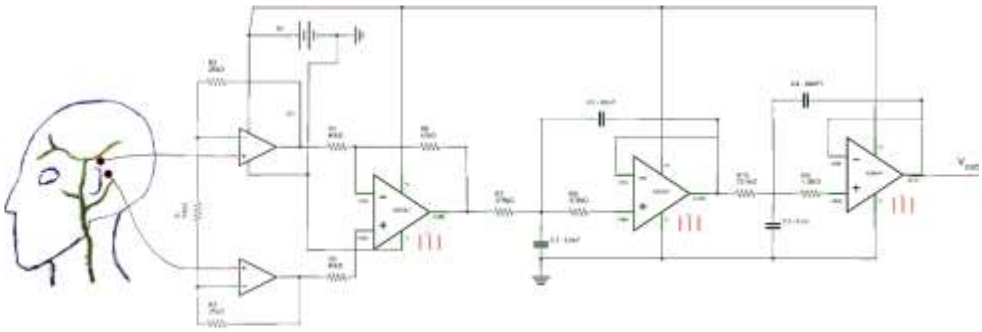

Figure 22: Electrode test circuit

As it can be seen in the figure, the electrodes have been attached with some distance to each other around the ear. The possible space for this was limited due to the requirement that the electrodes would have to be implemented into a temple. The voltage source during this test was an Arduino, which was also used to monitor the output, which then was sent via the serial protocol to a Laptop, which has previously been disconnected from the powerline in order to diminish the 50 Hz noise. In figure 23, the resulting output has been plotted using Excel. Three notable observations can be made from this graph: First, there seems to be a high-frequency noise present, which can not be fully ruled out by the low-pass filter and has an amplitude of around 20mV. The frequency is about 105 Hz. Another potential noise signal can be found at 32Hz. Second, using a sliding average, a 1,1 Hz signal can be found. Based on the frequency, this may be an ECG signal, but two points disagree with this hypothesis, as the waveform lacks the notable QRS complex of an ECG, which might of course only be covered by the noise. Furthermore, taken that the filtering only has minimal effects on this frequency and a monitored amplitude of 40mV, the original amplitude can be calculated to be around 0.08mV, which does not agree with the expected signal strength of up to 1mV. All in all, the data proves to be hard to analyze, especially if automated.

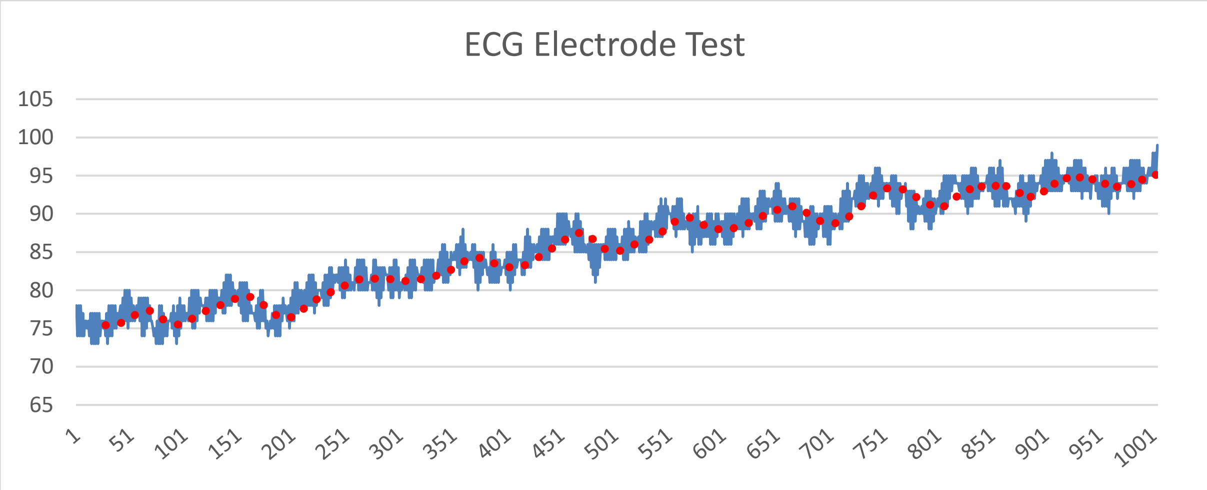

Figure 23: ECG test results; ms on x, mV on y

Optical

Optical heart rate sensing is done by the use of a led and a light sensor next to it. With this configuration and the earlier mentioned low light reflective properties of oxygenated hemoglobin, changes in blood flow can be monitored and a pulse rate can be measured, which is congruently to the heart rate. First tests using the Arduino compatible Max30100 sensor have shown promising results. An advantage of this technique is less noise proneness and good results on many locations on the body. Filtering of the signals acquired by this sensor happens in the software, for example by setting the reading frequency and by use of moving average windows.

However, due to the changing resistance within the blood vessels, according to Schäfer and Vagedes (2013), pulse rate variability sometimes is found to not sufficiently represent heart rate variability, especially with the subject not at rest. This needs to be tested if optical heart rate sensing is the chosen option.

Functional Specification

The following section aims to elaborate further on the design of the system. This includes not only the look of the system, but also which sensors and systems are used. Two possible design solutions have been thought of over the course of this phase. They both differ a bit in the setup and have their own advantages and disadvantages.

The first design can be seen in figure 24. This concept can be seen as a flexible sleeve made from silicon, which includes the electronics and hides them in an aesthetically pleasant way. The sleeve can easily be put on one of the temples, allowing for a fast setup on new glasses.

Furthermore, the system can quickly be taken off for data acquisition. Charging in this design could either be done by switching out battery packs once a day (possibly during the normal physiotherapy sessions) or on a docking station, which could serve as a nightstand for the glasses. As this yields the problem of having to remember the station, the docking station could be made into a normal spectacle case and include wireless charging. This design's advantages are a great adaptability and a quick setup for the use. The disadvantages on the other hand are first the bulkiness of the sleeve (it would probably be very visible) and second the positioning, as such a sleeve might easily shift on the temples.

Figure 24: Clip/Slide-On System

The second design option is sketched out in figure 25. This design makes use of the fact that most spectacle temple hinges are somewhat standardized. Therefore, it could be possible to switch out one of them with as little effort as turning a screw. This brings the same advantages as the first design but improves the reliability of the sensor staying on the spot intended. Furthermore, the aesthetics might be improved, as the temple is intended to have no obvious electronics on the outside, and instead look visually appealing. This design involves the part behind the hinge being separable from the glasses themselves, allowing for an easy switching of modules, battery change and data acquisition. Alternatively, the same station from the first design could be used for overnight charging. The main downside to this design would be the change in look of the glasses, which would be a result of the asymmetrical temples. Potentially this could be changed by replacing both temples for the duration of stay, one with a sensor bar and the other one with a fitting dummy.

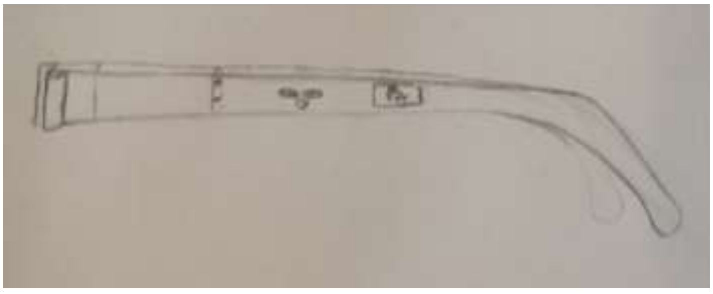

Figure 25: Smart Temple Sketch

Whichever design will be chosen during the realization phase, both share some considerations, which will be elaborated on in the following paragraph. While the prototype uses an internet connection for data transmission to a third party server, this is unlikely to be the case in the final product. This is due to data regulations and concerns within the medical sector. Especially due to the sensitive data on the health status of patients, it should be paid attention to the data transmission, which should be securely encrypted and stored on local servers.

A second decision has been made on the heart rate sensor choice. While proper ECG readings require electrodes for accurate results, it has been found challenging developing a reliable ECG circuit fitting in the prototype. Over the course of the research, the built electrodes in combination with the presented circuit and measurement location proved to be highly unreliable. While in some cases the readings gave some signals that could be interpreted as heart readings (figure 23), in other test cases only noise such as in figure 26 could be observed. Here it is visible that no heart rate signal could be taken out of the values, and no explanation for the inconsistency in observed values could be found. Thus it has instead been decided to use an optical sensor for heart rate sensing, as it yielded promising values for heart rate variability in previous tests and was more fit for this project convenientwise.

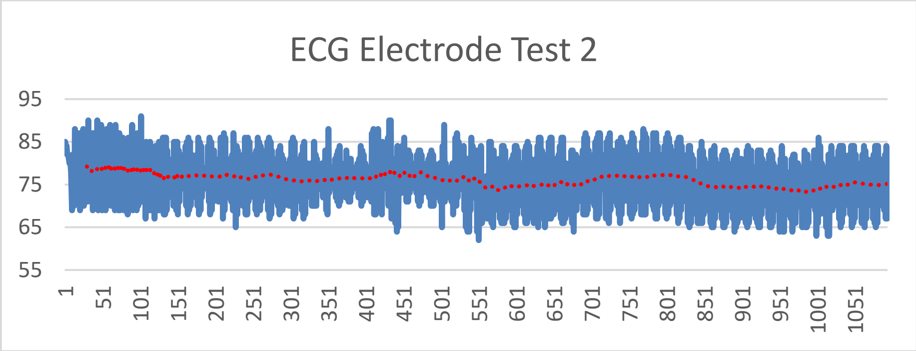

Figure 26: Example electrode test run; ms on x, mV on y

In a first prototype 4.7V 750mAh battery packs are being used. Furthermore, the energy rating of the Spark Core with Wi-Fi enabled is 30mA. Together with the MAX-30100 optical heart rate sensor (25mA) and the GY-521 gyroscope/accelerometer (5mA), this gives a total power consumption of 60mA. Thus, one battery pack gives a supposed battery life of almost 13 hours, which can be extended by switching off the Wi-Fi module of the controller.

VI – Realization

As the final prototype was being realized, a number of issues had to be tackled. The hardware itself was assembled easily, but the placing had to be determined and the programming needed to be done. The following chapter will therefore elaborate on the building process, the considerations and decisions made during this and issues that came up.

Prototype components

The following paragraphs will describe the hardware components used to assemble the prototype. After this, the components prices will be listed to give a cost estimation of the production costs of a potential commercial product.

Particle Core

The Core, as shown in figure 27, was developed by Particle, former Spark, and is a microprocessor unit with a mounted Wi-Fi chip. The internal processor unit itself runs at a 72 MHz speed and has an internal storage space of 128 kb flash memory with an additional 20kb of SRAM. Programming is completely done over the internet with an adapted version of the Arduino programming environment, allowing for testing on Arduinos. Furthermore, a framework for retrieving data over the internet is provided. The energy consumption of the board with Wi-Fi enabled is approximately 150 mA. When the Wi-Fi is disabled, this drops to 30-40 mA, while the deep sleep mode minimizes consumption to a total of 187 µA.

Figure 27: Spark Core; Source [15]

RCWL-0530

The RCWL-0530 breakout board, depicted in figure 28, is a rather cheap but reliable option using the Max-30100 optical heart rate sensor. Transmission of data is done via the I2C protocol, allowing for reliable communication between the processor and the sensor. Next to normal heart beat detection it is able to estimate the SpO_2 value and brings an on-board temperature sensor. Its operating voltage is fitting to the Core at 3,3V with an operating current of 50mA and a particularly small shutdown current of 0,7 µA.

Figure 28: RCWL-0530 sensor; Source [16]

GY-521

The MPU-6050, which is the sensor built into the GY-521 (figure 29) breakout board, is a considerably cheap sensor given the fact, that it combines both an accelerometer and a gyroscope. Furthermore, it has one 16bit analog to digital converter on each of the three axis channels, allowing for simultaneous sampling. It furthermore has a digital motion processor built in, which can be programmed to do complex calculations on the chip, reducing the load on the microcontroller it is used with. The operating current is fairly low with 3,6mA, while the standby current only is 5 µA.

Figure 29: GY-521 board; Source [17]

Costs

The individual costs and total costs are being listen in table 1. It is to note, that these were only the costs for the prototype parts as being bought individually. When producing the product on a larger, certain costs may e subject to significant changes. Especially the microcontroller will most likely be replaced by a printed circuit board with only a processor, tailored to the needs of the product. On a larger scale, this is expected to drastically reduce the production costs.

Table 1: Prototype Costs

Component	Price
Particle Core	*17€*
RCWL-0530	*6€*
GY-521	*6€*
Silicon (casing)	*3€*
Various components	*4€*
Total	36€

Functional decomposition

In figure 30, the processes involving all entities in contact with the system are laid out. The primary user (the patient) does not actively interact with the system but instead wears it as a regular piece of accessory. All the data from the sensors first gets processed and then regularly sent to the webpage, which acts as the main interaction interface for the second user, the therapist. Here all data is collected over time and presented in an easily accessible manner.

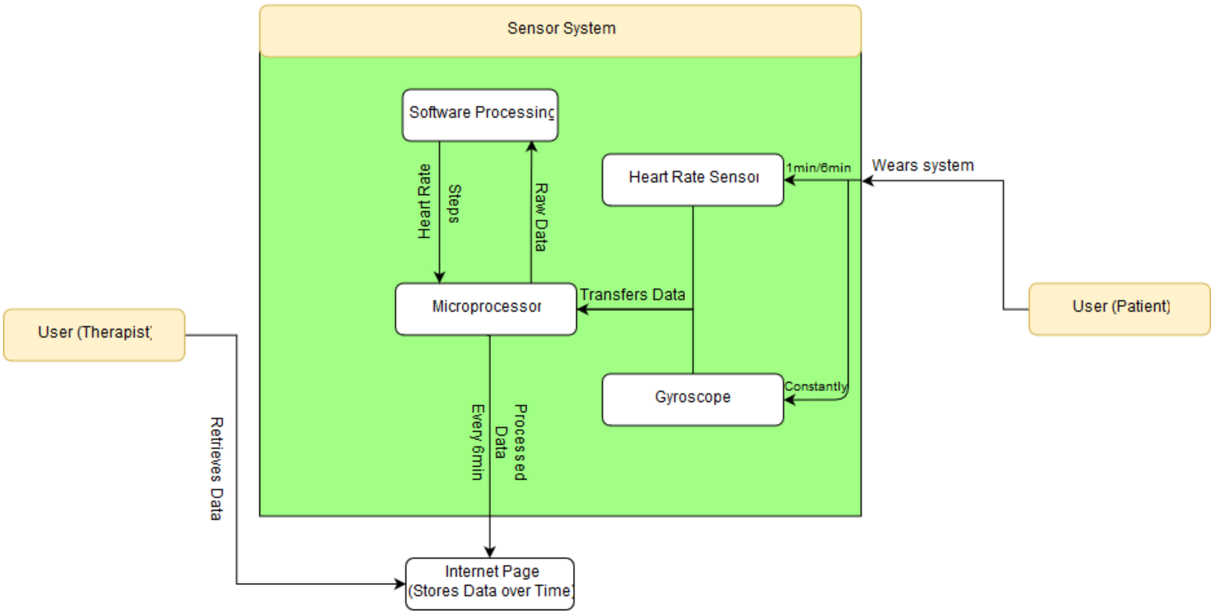

Figure 30: Decomposition of the proposed system

Algorithms

The following section will elaborate on the software side of the prototype. The full code can be found in Appendix A. First general considerations and after this, the heart rate and heart rate variability estimation algorithms will be explained. Third, the acquirement of the activity measure, the steps taken, will be described.

The frequency of measurements taken was an important decision, which had to be made. While the activity needs to be measured constantly in order to detect also short activity periods, the heart rate artifacts are not as important to measure constantly, which allows for the heart rate sensor to be switched off periodically to save energy but to also lessen the load of meaningless data. For this, a roughly 17% measurement to non-measurement time relationship has been chosen, which results in a one-minute measurement window every 6 minutes, 10 measurements per hour. During this one minute, heart rate and heart rate variability are measured using the algorithm presented in the next section. This led to a repeating, six-minute cycle, which can also be used to disable the Wi-Fi module for 83% of the time, greatly reducing total power consumption. Activity however will be measured constantly, ruling out the option of the most energy-efficient deep sleep mode.

The heart rate sensor, as explained earlier, uses an LED and a photodiode. The return values are internally calculated and transferred using the I2C protocol. They are therefore not limited to the 0-3.3V range of the Core, but instead can range from 0 to (theoretically, as the number is represented by 2 bytes) 65.535. Upon mounting the sensor behind the ear, most values obtained range from 17.000 to 21.000. An example diagram of sensor values taken are plotted in figure 31. The heart rate is clearly visible, but sometimes a base shift has been observed. The most significant artifact of a heartbeat is the steep drop in value, which therefore has been chosen to be the trigger for a heartbeat. As soon as the value difference of two measurements, being 10 measurements apart, is higher than a threshold, the peaking value will be searched for in the neighboring values and the time it has been taken will be saved. For the general heartbeat, it is looked at how many beats have been observed in the minute of measurement. However, for reducing the impacts of false-negatives and false-positives, the successive period is compared to the average and huge heart rate variabilities will be corrected by either adding an 'imagined' beat or removing a supposed false-positive.

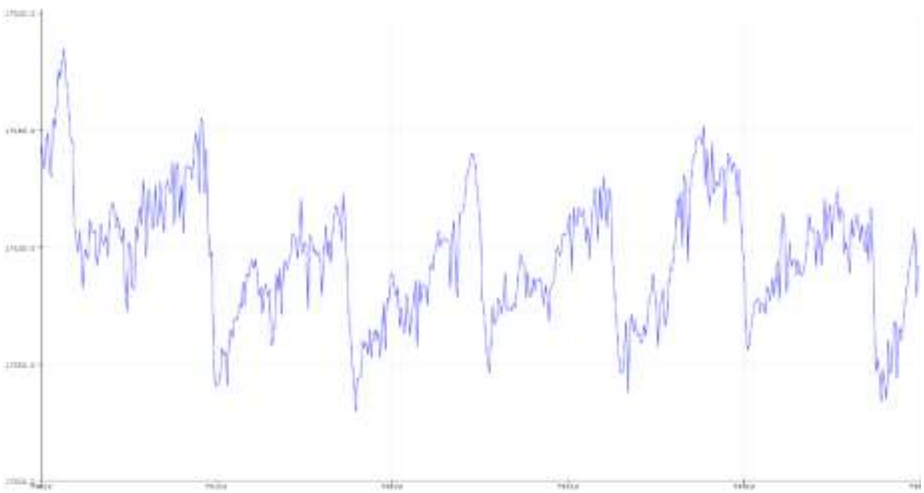

Figure 31: Heart Rate Sensor Data; x:time, y:return value

In order to test the algorithm, a test with the following setup is conducted: The programmed microcontroller with the heart rate sensor was set up in place (at the temple) and used to measure a total of 60 beats. The resulting beats with respect to time are plotted in figure 32. It comes clear, that one beat has been missed between the beats 17 and 18, where the period of the consecutive beats is 75% longer than the previous and even 102% longer than the next one. But on a closer look one can also observe smaller variations, for which the pulse rate variability (PRV) analysis yields a PRV RMSSD value of 71ms. This has still to be tested on the congruency with HRV, as no reference has been used during this test, but with the mean HRV value for an 18 to 25-year-old male being 68 [18] and the tests being run on a 22-year-old male, this looks like a promising result.

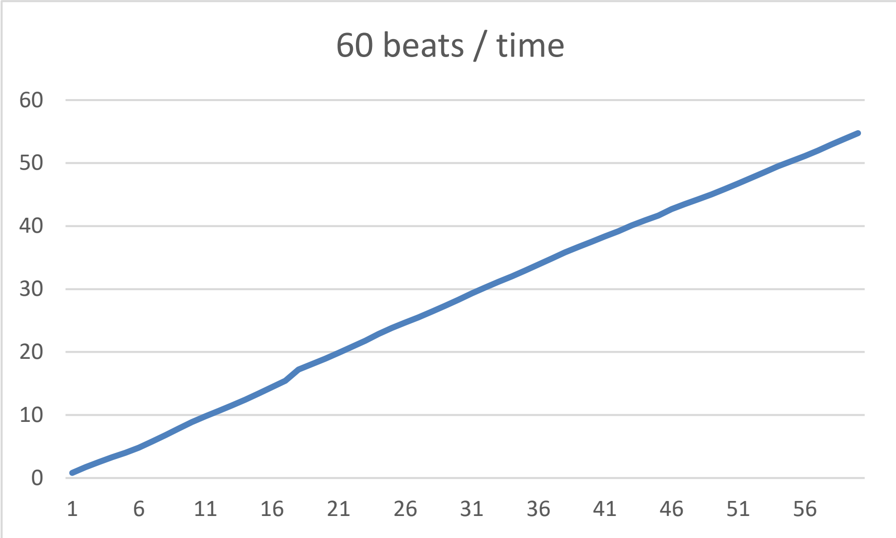

Figure 32: 60 measured beats plotted against time

The next signal to be measured is the activity of the wearer, for which the step count has been chosen to be the measure. To achieve this, a combined gyroscope and accelerometer has been included in the prototype. Due to movement noise, this has proven to be more difficult than anticipated earlier. After all, the gyros z-value has been proven most reliable. For detection, a moving average of the last 11 sensor readings is compared to a moving average of the last 6 ones. These two moving average variables are subtracted from each other, resulting in the plot in figure 33. Advancing on this, two threshold triggers are being established: 1500 and -1500. In order for a movement to be declared a step, first the upper trigger will need to be reached and then the lower one a few milliseconds after this. As it can be seen in the plot, this resulted in a quite reliable step recognition. To test the reliability of this algorithm, a test has been conducted in which the sensor was put into place and a total of 25 steps were taken on a flat surface, which has led to a correct recognition of 92% of these 25 steps. Due to the fact, that this data is mostly supposed to be of qualitative value rather than quantitative, the algorithm is considered well enough for including in the prototype. During further testing, it can furthermore be looked at the change in the gyros x-value due to the slight leaning of the body during walking.

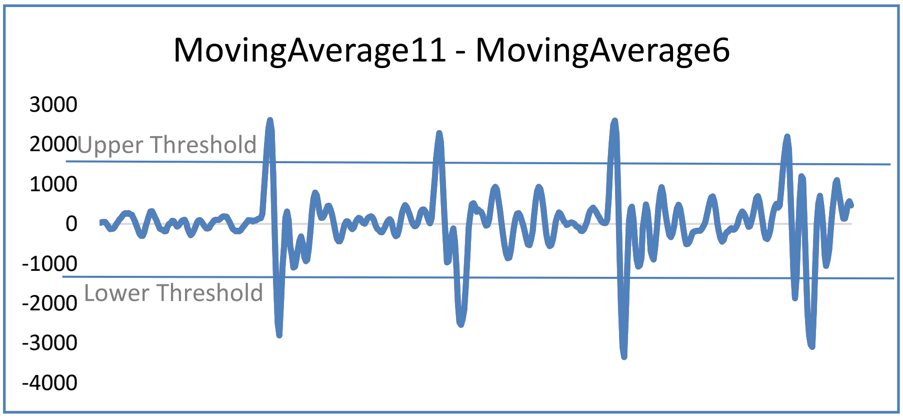

Figure 33: MovingAverage11 - MovingAverage6 of 4 steps plotted against time

Prototypes

The following section will focus on describing the various prototypes that have been built until the final version was ready. Every prototype gave valuable information on what needed improving and what was good as it was. The first prototype, depicted in figure 34, was the first to feature the silicon casing that has been chosen as the prototype mantle. While it ran quite well, the positioning of the device was quite poor, as it sat all the way back at the temple. This on the one hand was experienced as unpleasant around the ear and on the other hand gave the inconvenience of a lot of asymmetrical weight at the back of the glasses.

Figure 34: 1st prototype

Thus, the second version (figure 35), which had been purely designed for cablebound testing, was placed further at the front, bringing a significantly raise in pleasantry, also because the mass of the silicon was reduced drastically. However, now the heart rate sensor was too loose and would not always stick to the right spot on the artery. Furthermore, this version did not include a place to put the battery pack.

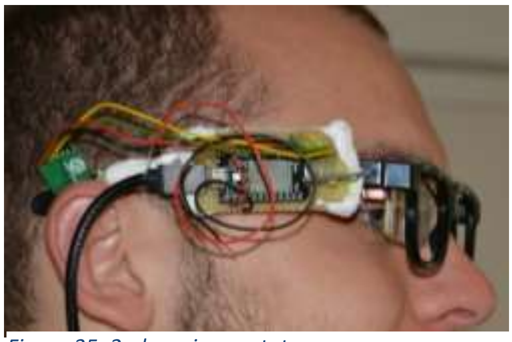

Figure 35: 2nd version prototype

The third and last version of the prototype (figure 36) intends to better out the weak spots of the previous version and deliver full functionality. Compared to the last version the weight increased slightly due to the addition of a battery pack, which is placed close to the ear, as this is the safer and more convenient spot to increase the weight compared to the front, where the weight would bear on the nose. Furthermore, the heart rate sensor has been fixed in place using more silicone along the temple. The last improvement happened on the software side by the implementation of a database and a visual webpage. The measurements taken are stored online in a database, from which the data is taken by the webpage and visually represented in an easy to recognize way. Figure 37 shows the graph from the page with some example data obtained during a test.

Figure 37: 3rd version prototype

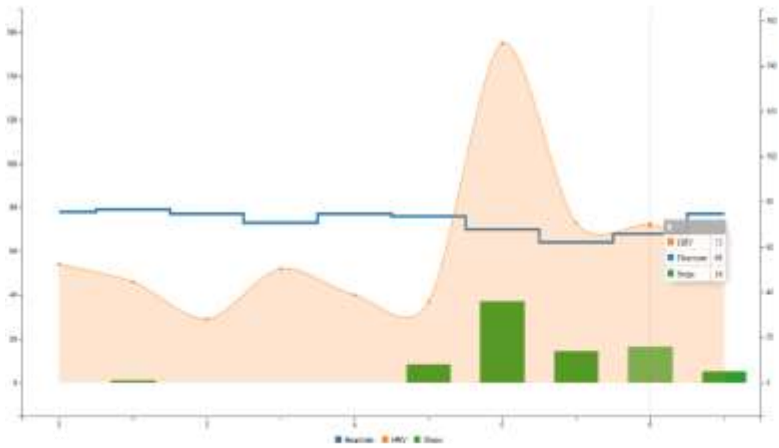

Figure 36: Online data visualization

VII – Evaluation

Evaluation Plan

Stage I Testing

Following the Framework for the Evaluation of Telemedicine as proposed by Jansen - Kosterink, Vollenbroek – Hutten and Hermens (2016), the sensor system will first have to be tested on accuracy and reliability in the first stage of a four-stage program. This is to ensure that a system, that is up for further development, is in fact able to reliably deliver the data it intends to.

In order to test the system on this, a critical case study is being designed and conducted with the aim of assessing the quality of data obtained from the prototype being presented in the last chapter. For the study, a total number of three participants will be selected (n=3). In this phase, testing will be done on persons from various ages, ranging from 20 to 50. The selected participants will, one at a time, wear both the system prototype as well as a Zephyr Belt to monitor heart rate and a smartwatch to track steps taken. These two commercial systems will act as the measures of the test. Furthermore, for the duration of the test, the pausing cycle of the system will be switched off. This will be done to receive more data from the system, while keeping the test short at the same time. As the pausing cycle is not expected to change the results of the system but only acts as a power saving mode, this can be done without influencing the meaningfulness of the test. The participant then is asked to take a walk of approximately 10 minutes. After this, the satisfaction with the system will be tested using a questionnaire. Due to the fact that the system will require little to no interaction, the test level satisfaction is the more interesting level opposed by the task level satisfaction. For measuring it, the *System Usability Scale* will be used, the questionnaire can be found in Appendix C.

The data obtained by the systems then will be analyzed and checked for correlations, for which the *intraclass coefficient* will be used. According to the Koo and Li (2016) and based on a 95% confident interval, a value between 0,75 and 0,9 can be considered as an indicator for a good reliability, while everything above 0,9 is an excellent one. Using this and the fact that the step count is supposed to be more of an indicator, while HR and HRV are also quantitatively important, for the former a good and for the latter an excellent correlation will be hoped to be met. However, while the heart rate needs to be accurately measured by the system, HRV correlations may be enough to give an indication of changing health status without accurately yielding the same results. To test for this, a *Pearson correlation test* will additionally be performed on the HRV results, which, opposed to the intraclass coefficient, tests solely for correlation without being influenced by agreement between the measurements.

Results

Functional

Using the previously described test schematic, the test has been conducted on a total number of n=3 participants. The detailed results can be found in Appendix D. Some of the results most notable are being described in the following.

Heartrate

A 20-minute test resulted in the heart rate values plotted in figure 38. In blue the heart rate as picked up by the glasses can be seen, while the red and green plot represent the reference heart rate picked up by the Zephyr belt and the moving averaged value, also by the Zephyr, respectively. The interesting fact here gets introduced by the purple line representing the number of steps done since the last reading. It is clearly visible, that as the activity rises, the error, or difference from the reference measurements, of the heart rate readings performed by the glasses rise. A Pearson correlation test on the error and the number of steps gave a value of -0,45. This does not express a moderate correlation yet but is enough to hint at least some interactions between the two. However, the intraclass correlation test performed in SPSS on the three datasets gave ICC values from 0,686 to 0,883, mostly indicating a good correlation between the two measurement devices. Due to the fair correlation between the error of the glasses and the steps, two more ICC values have been calculated, one for the state with the subject at rest and one for while the subject is walking. The two values did differ slightly, with both yielding a substantial correlation value, the former one of 0,763 and the latter resulting in a 0,631. The scatterplot of these two sets is depicted in figure 39, where it can be seen that the measures taken in the active state are slightly more distributed than the ones taken during rest.

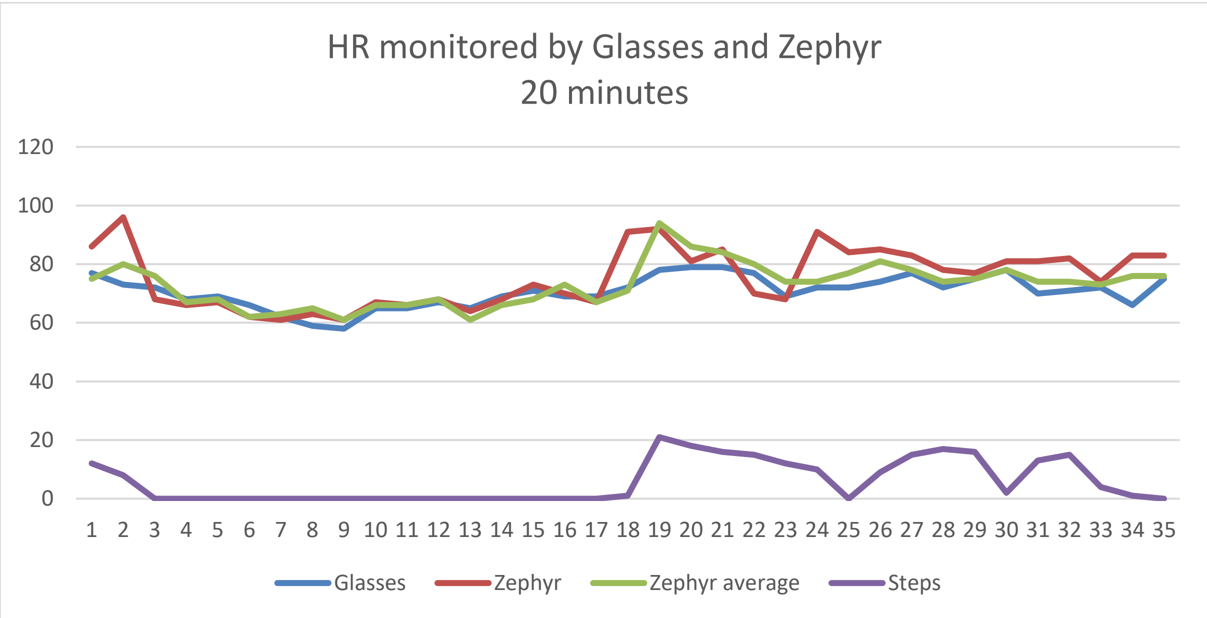

Figure 38: HR measurements & Steps

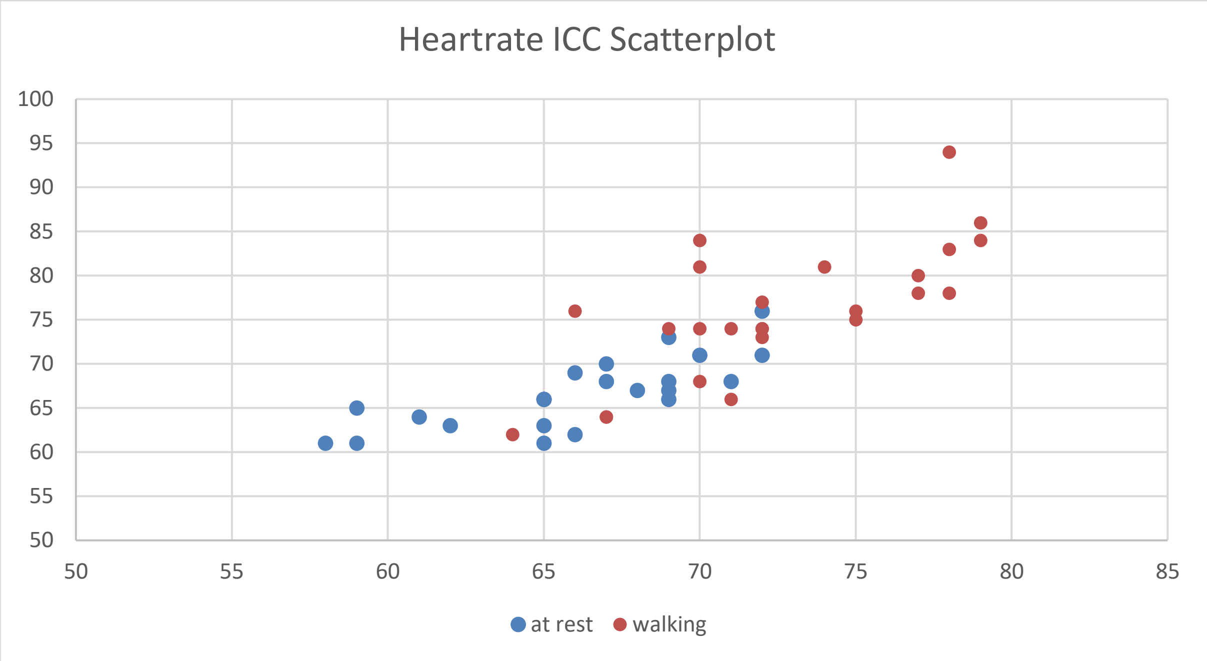

Figure 39: HR ICC Plot

Heart Rate Variability

Within the same test run, the PRV/HRV readings as plotted in figure 40 have been observed. Again, the activity level, or steps taken, seemed to have decreased the accuracy of the glasses. Therefore, the HRV as picked up by the Zephyr was subtracted from the HRV returned by the glasses in order to get the error of the glasses. This error was used in another Pearson correlation test together with the steps taken, which yielded a value of 0,344, hinting a fair correlation. Thus, in order to visualize this, activity is plotted together with the other two measured values. Also, during one test, a correlation test between PRV value and steps yielded a moderate agreement value of 0,45. The conversion from read PRV values to actual HRV values proved to be more difficult than anticipated, resulting in a Pearson correlation value of approximately 0,35. However, a huge difference between active and inactive states has been observed here: While the correlation test yielded a value of 0,63 during rest, indicating moderate correlation, during actively walking around this correlation dropped to 0,2. A fact to mention here as well however, is that the PRV and HRV measurements, if averaged over a longer time, were very similar with a maximum difference of 15%. Furthermore, figure 40 contains a moving average of the last two measurements, effectively smoothing the curve, which resulted in an overall (both states of active and inactive) moderate Pearson correlation value of 0,45. The ICC scatterplot can be seen in figure 41. As with heart rate, the values measured at rest are quite packed together, while the ones taken during activity are spread out quite far.

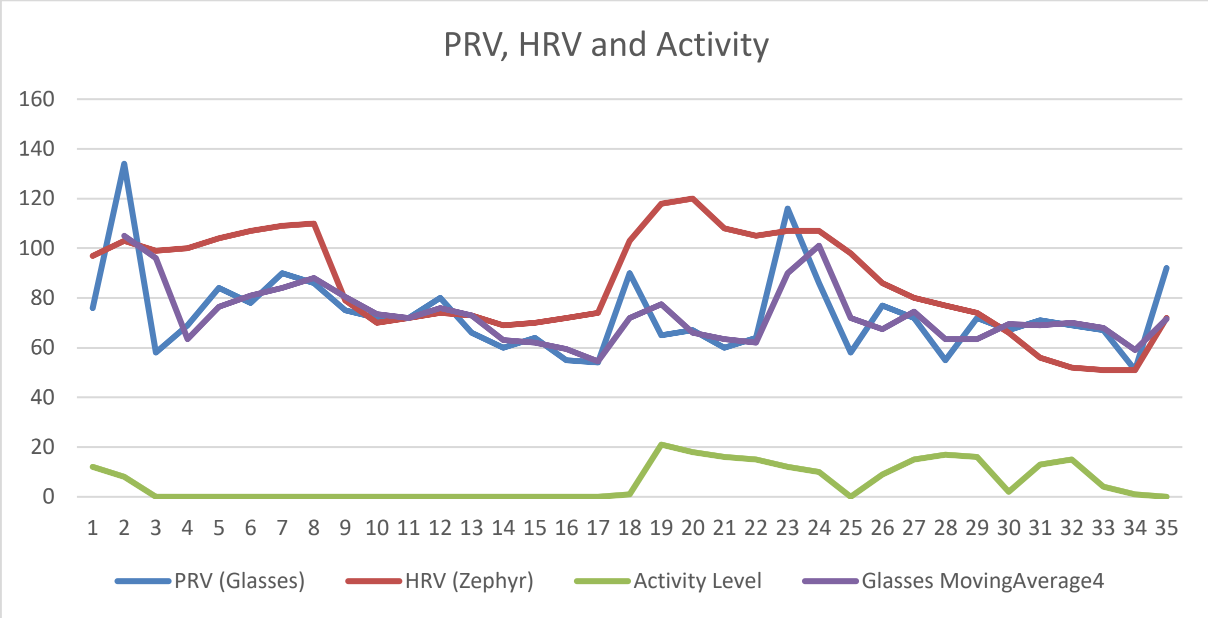

Figure 40: PRV, HRV and steps plotted

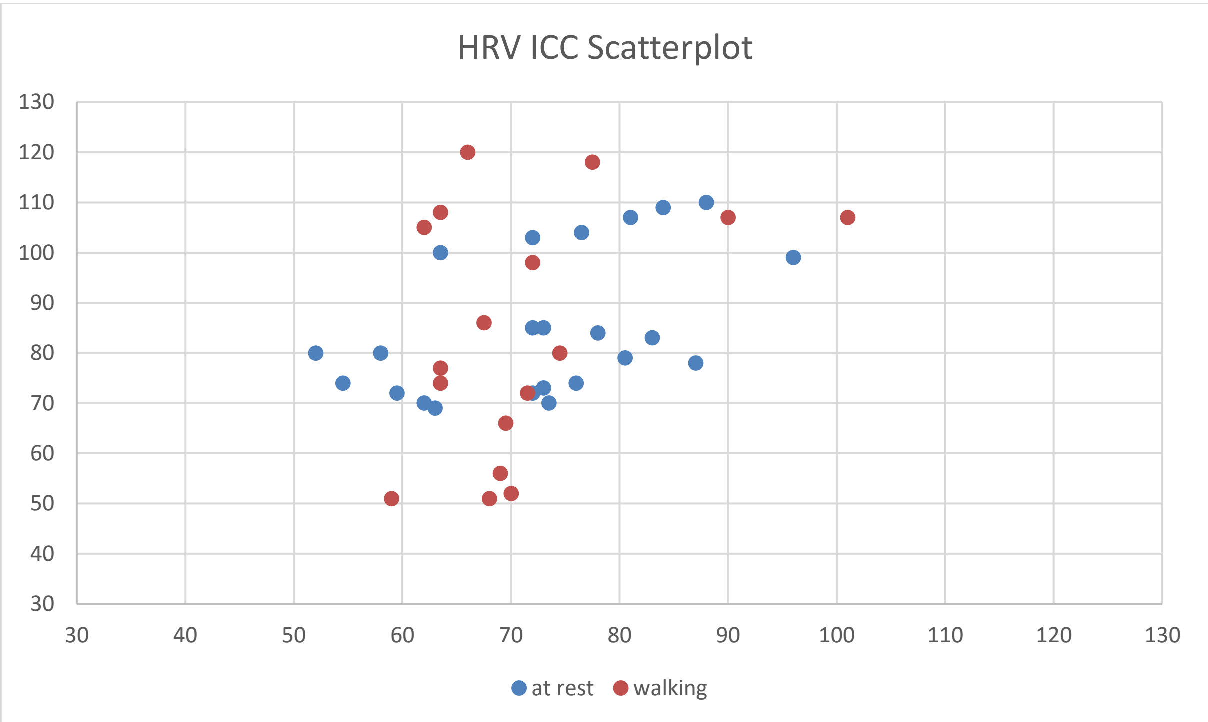

Figure 41: HRV Scatterplot

Activity

As the smartwatch, which was used (Skagen Connected), can only store and display the total number of steps, the data obtained can only be compared with respect to the total level at the end of the test. All in all, the glasses tend to overestimate the number, during the tests the glasses had a positive error of 20% on average.

UX / System User Scale

The *system user scale* questionnaire, which has been filled out by two of the three participants yielded a mean value of 73,8 out of 100 points. Notably here is that the scores deviated quite far from each other, the first giving a score of 85, while the second only rated it as a 62,5.

Discussion

Heart Rate

On the functional side of the test, the achieved results give mixed feedback. The heart rate measured by the glasses was often very close to the reference measurement taken by the Zephyr, however, deviations did occur. This is expected to be caused by both software and hardware. Optical heart rate sensors have proven to be very accurate when it comes to heart rate and if measured at a good spot. Good readings above the ears indicate the placing is not the problem when readings are off but instead it might be a problem when the glasses move. This can happen due to movement of the head, for example while walking and false heartbeats can be detected, or the sensor might shift out of place. Here, a small array of sensors might increase general reliability. Softwarewise, the algorithm might need polishing or redesigning in order to better the estimation. However, for a prototype, the mostly at least good correlation between heart rate and measured heart rate can be considered as a positive proof of concept.

Heart Rate Variability

Heart rate variability measuring on the other hand has been proven to be rather troublesome, which is not necessarily a problem of the measurement location. It is more likely, that the problems are caused by the previously, in the literature research mentioned, additional effects on pulse rate variability such as movement or breathing, which effect the resistance within the blood vessels and thus influence the pulse rate variability independently from the heart rate variability. Especially when being active, the conversion between PRV and HRV dropped to non-acceptable levels. Values obtained at rest tend to fluctuate quite a bit as well, but especially when averaged, the values seem to correlate. Due to the fact that the device is only a prototype with commonly available, cheaper electronics used, this will be considered a generally good result. Larger changes in HRV, for example when it lowers significantly, are expected to be picked up, while the use of better developed sensors will raise the accuracy.

Both of these previous artifacts were influenced by walking. As mentioned, one possible explanation for this are false positives due to movement of the glasses as well as false negatives due to the sensor shifting out of place. While the mentioned sensor array would minimize false negatives, false positives are expected to remain the same problem. The best way of tackling this issue would be keeping the sensor in place, which can be done via two main ways. The first one would be assuring proper pressure, which is less achievable using the current prototype, while in case of the second design choice this could be easier done adapting the hinge design. The second way would be the use of an adhesive material, which would lessen the movement of the sensor. On the other hand however, would this most likely cause skin irritation on a longer use period, as it has been observed for wet electrodes, or require help for putting on or taking off the system, which would seriously lessen the convenience of the system, especially with the choice of integrating it into the glasses, an everyday object likely to be put on and off a couple of times over the day.

Activity

The steps were the last artifact to monitor and did not quite yield the most accurate results. This is especially due to the fact, that head movements already had a chance on being classified as steps. This problem can on the one hand be solved by better algorithms in the future, for example by including a second axis to be monitored and needed for correct classification. On the other hand were the steps mainly meant as a measure of activity level, and are therefore only needed as an indicator, which is why for the prototype the achieved results are being seen as a proof of concept.

System User Scale

When it comes to the user experience, the system user scale is often used, but is of only limited use for comparing the product with existing solutions and is less meaningful on its own. Often it is used as a tool for comparing different versions of a product by looking at an increase or decrease in score. During this test, the deviation between the two questionnaires is the most obvious conspicuity. However, when taking a closer look at the individual answers, one tester generally seemed to answer more neutral than the other, without really giving negative points. Furthermore, these results have to be interpreted critically, due to the fact that the testing subjects were personally associated with the test leader, which might have influenced the scores. This test is advised to be rerun using more testers (n>9) and possibly also an improved version of the prototype in order to get a more meaningful result. The two main issues that can be taken out of this test are that people do not feel that confident using the system and that they do not necessarily see themselves using it more frequently.

Due to the fact that the testers themselves did not have to interact with the system at all, a possible explanation for the confidence issue can be that they were intimidated by the bulky prototype, which did not try to hide the electronics. To test this explanation, in the next version the prototype should be reduced in size and have the electronics less surfacing. While the same changes could also solve the other issue, solving this could also involve a better clarification of the benefits of the system being used on a long term.

All in all, the test conducted helped to discover flaws and weaknesses of the prototype in its current state, but proofed the concept to be functional and valuable at the same time. Further development on the hard- and software side is advised, which should be followed by a test setup with a higher number of participants. Correlation values and system user scale scores should then be compared to see if progress was possible to make.

VIII – Conclusion

The original research question of "*How can a smart system for monitoring elderly hip patients be implemented*" yielded a number of commercially available products on the market, which seem suitable for the given purpose. Especially the Hexoskin Smart Shirt delivers accurate sensors within a washable shirt and a detachable processing unit.

For novelty's sake the question has later been specified to "*How could a head worn health tracking device be implemented in the hip-fracture rehabilitation process"* . To this purpose a concept of a smart spectacle temple has been designed and a prototype was made to test the feasibility of such a product. Especially the use of optical heart rate sensors proved to be rather problematic for one of the key artifacts, namely the heart rate variability, with a substantial decrease in accuracy when monitoring a person during a physical activity. The concept however shows potential for further development and can help getting insightful data to therapists, effectively improving the rehabilitation quality for patients.

IX – Future Work

If the project is intended to be further developed and turned into an commercial device, a couple of recommendations of research directions can be given. As mentioned in the evaluation section, further testing on a larger group of participants may be advisable before advancing to stage 2 testing (following the cited evaluation framework), in which it would be focused on the potential effect of the system.

Dry Electrode ECG

In order to achieve more accurate heart readings, it is advisable to do testing and developing on dry electrode ECG measurements taken behind the ear. While this is generally not a conventional place for ECG measurements, existing research with wet electrodes has shown potential. Importance here has to be put on the filtering out of EMG signals, as these can reach up to 30mV and may therefore be much stronger than heart readings.

Activity Data

Another important step would be the in depth analysis and classification of gyroscope/accelerometer data in order to improve gait analysis/detection and introduce posture detection, as this has only been achieved at a fundamental level while better classification of the data can further improve the impact of the system.

Design Choices

Furthermore, the actual aesthetics of the system have to be established, as they have been left out of this paper for the most part. Two different design options have been proposed, namely the sensor sleeve and the full smart temple. Both bring their own advantages and disadvantages, which may be further explored in prototyping and testing, especially with respect to sensor data accuracy.

Security

Before being able to be applied in the medical sector, the system will need a complete overhaul with respect to security. While the 3rd party microcontroller used in the current version of the prototype transmits data encrypted using the AES/RSA protocol, data is still stored and handled on external servers. It might be worth developing or researching in the existence of Wi-Fi or UMTS enabled microcontrollers which allow for data retrieval without a middle man.

Robustness and Size

When aiming for a commercial product, the system needs to be of reduced size and weight while also be more robust. The current prototype uses large sensors and electronics which are openly visible. A printed circuit board needs to be developed in order to decrease size and maximize production effectiveness. At the same time this would enable the development of a proper casing in one of the two design directions mentioned.

Hearing Aid

The idea of a smart hearing aid as presented in the ideation section could be worth investigating further as well, as a cooperation with a company might be easier to achieve in this sector while still being a common accessory in the target group. Also, such a system is expected to be less prone to movement noise while still using essentially the same technology and location. Furthermore PRV readings taken closer to the core of a body (e.g. in the auditory canal), have found to correlate better with the heart rate variability.

X – References

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Appendices

Appendix A – Particle Code

```
#include <MAX30100.h>
#include <math.h>
// Sampling is tightly related to the dynamic range of the ADC.
// refer to the datasheet for further info
#define SAMPLING_RATE                    MAX30100_SAMPRATE_50HZ

// The LEDs currents must be set to a level that avoids clipping and maximises the
// dynamic range
#define IR_LED_CURRENT                   MAX30100_LED_CURR_50MA
#define RED_LED_CURRENT                    MAX30100_LED_CURR_27_1MA

// The pulse width of the LEDs driving determines the resolution of
// the ADC (which is a Sigma-Delta).
// set HIGHRES_MODE to true only when setting PULSE_WIDTH to MAX30100_SPC_PW_1600US_16BITS
#define PULSE_WIDTH                    MAX30100_SPC_PW_1600US_16BITS
#define HIGHRES_MODE                     true

//Step count vals
const int MPU_addr = 0x68; // I2C address of the MPU-6050
int16_t AcX, AcY, AcZ, Tmp, GyX, GyY, GyZ;
bool inStep;
int stepCount;
int oldStepsCount;
long inStepCount;
int zVals[20];   //Important

//Heart rate vals
// Instantiate a MAX30100 sensor class
MAX30100 sensor;

#define OFFSET 20000
#define UPPERTIMEOUT 500
#define LOWERTIMEOUT 1500
#define BEATVALUE 170
#define BEATCOUNT 25
#define LOWERBOUND 0.8
#define UPPERBOUND 1.4
unsigned long beats[BEATCOUNT];
int values[20];
unsigned long milliVals[20];
unsigned long uptimeCount;
unsigned long uptimeTimer;
int beatCount;
unsigned long timer;
int beatsPM;
double prv;
bool led;
bool heartscan;
int sensorval;
int clicks;
void setup()
{
   Serial.begin(115200);
   Serial.println("initializing");
  //Step count stuff
   Wire.begin();
  Wire.beginTransmission(MPU_addr);
  Wire.write(0x6B);  // PWR_MGMT_1 register
  Wire.write(0);     // set to zero (wakes up the MPU-6050)
  Wire.endTransmission(true);
  stepCount = 0;
  inStepCount = 0;
  for(int i = 0; i<20; i++) {
   zVals[i] = 0;
  }
   Serial.println("Steps initialized");
  //Heart rate code
  pinMode(D7, OUTPUT);
```

```
  heartscan = true;
  led = false;
  clicks = 0;
  beatsPM = 0;
  prv = 0;
  uptimeCount = 0;
  uptimeTimer = 0;
    Serial.println("variables initialized");
  Particle.variable("UptimeOnAccu", uptimeCount);
  Particle.variable("BPM", beatsPM);
  Particle.variable("PRV", prv);
  Particle.variable("Sensor", sensorval);
  Particle.variable("Total Beats", clicks);
    Serial.println("publishVars initialized");
  digitalWrite(D6, HIGH);
  for (int i = 0; i < BEATCOUNT; i++) {
    beats[i] = 0;
  }
  for (int i = 0; i < 20; i++) {
    values[i] = 0;
  }

  // Initialize the sensor
  // Failures are generally due to an improper I2C wiring, missing power supply
  // or wrong target chip
    Serial.println("Initializing Sensor (begin)");
  if (!sensor.begin()) {
    for (;;);
  } else {
  }

  // Set up the wanted parameters
    Serial.println("Initializing Sensor (parameters)");
  sensor.setMode(MAX30100_MODE_SPO2_HR);
  sensor.setLedsCurrent(IR_LED_CURRENT, RED_LED_CURRENT);
  sensor.setLedsPulseWidth(PULSE_WIDTH);
  sensor.setSamplingRate(SAMPLING_RATE);
  sensor.setHighresModeEnabled(HIGHRES_MODE);
  Particle.publish("Came online", "online now", 4320, PRIVATE);
    Serial.println("Begin");
    uptimeTimer = millis();
}

void loop()
{
  //Step count
  Wire.beginTransmission(MPU_addr);
  Wire.write(0x3B);  // starting with register 0x3B (ACCEL_XOUT_H)
  Wire.endTransmission(false);
  Wire.requestFrom(MPU_addr, 14, true); // request a total of 14 registers
  AcX = Wire.read() << 8 | Wire.read(); // 0x3B (ACCEL_XOUT_H) & 0x3C (ACCEL_XOUT_L)
  AcY = Wire.read() << 8 | Wire.read(); // 0x3D (ACCEL_YOUT_H) & 0x3E (ACCEL_YOUT_L)
  AcZ = Wire.read() << 8 | Wire.read(); // 0x3F (ACCEL_ZOUT_H) & 0x40 (ACCEL_ZOUT_L)
  Tmp = Wire.read() << 8 | Wire.read(); // 0x41 (TEMP_OUT_H) & 0x42 (TEMP_OUT_L)
  GyX = Wire.read() << 8 | Wire.read(); // 0x43 (GYRO_XOUT_H) & 0x44 (GYRO_XOUT_L)
  GyY = Wire.read() << 8 | Wire.read(); // 0x45 (GYRO_YOUT_H) & 0x46 (GYRO_YOUT_L)
  GyZ = Wire.read() << 8 | Wire.read(); // 0x47 (GYRO_ZOUT_H) & 0x48 (GYRO_ZOUT_L)
  moveZVals();
  zVals[19] = AcZ;
  if(movingAverage11()-movingAverage6() > 1500 && !inStep) {
      inStep = true;
      inStepCount = millis();
    }
  else if(movingAverage11()-movingAverage6() < -1500 && inStep){
      //Serial.print("Step at ");
      stepCount++;
      Serial.println(millis());
      inStep = false;
    }
  else if(inStepCount + 200 < millis()) {
      inStep = false;
    }
  //Heart rate
```

```
  if(uptimeTimer + 10000 < millis() && !heartscan) {    //300000
    Particle.publish("Still online", "Heartscan started", 60, PRIVATE);
    uptimeTimer = millis();
    heartscan = true;
    sensor.resume();
   // WiFi.on();
  }
  else if(uptimeTimer + 60000 < millis() && heartscan) {
      finishCycle();
  }
  uptimeCount = millis();
    uint16_t ir, red;
    moveMillis();
    sensor.update();
  if(heartscan) {
    milliVals[19] = millis();
    while (sensor.getRawValues(&ir, &red)) {
      moveVals();
    //   Serial.println(red);
      values[19] = red - OFFSET;
      sensorval = red;
      if (values[0] - values[10] > BEATVALUE && millis() > timer + UPPERTIMEOUT) {
        checkPeak();
      }
    }
    if (beatCount >= BEATCOUNT) {
      beatsPM = getBPM();
      prv = getVariabilityRMS();
      beatCount = 0;
      Serial.print("Beats per minute: ");
      Serial.println(beatsPM);
      Serial.print("Pulserate Variability: ");
      Serial.println(prv);
      Serial.print("Steps: ");
      Serial.println(stepCount);
      finishCycle();
    }
  }
}
//Step count code
int movingAverage6(){
    int retVal = 0;
    for(int i=0; i<6; i++) {
        retVal = retVal + zVals[19-i];
    }
    return (retVal/6);
}

int movingAverage11(){
    int retVal = 0;
    for(int i=0; i<11; i++) {
        retVal = retVal + zVals[19-i];
    }
    return (retVal/11);
}

void moveZVals() {
  for (int i = 0; i < 19; i++) {
    zVals[i] = zVals[i + 1];
  }
}

//_____________________________________________Heart rate stuff
void finishCycle(){
    Particle.publish("BPM", String(beatsPM), 60, PRIVATE);
    Particle.publish("PRV", String(prv), 60, PRIVATE);
    Particle.publish("Steps", String(stepCount-oldStepsCount), 60, PRIVATE);
    uptimeTimer = millis();
    oldStepsCount = stepCount;
    heartscan = false;
    resetValues();
    sensor.shutdown();
    //  WiFi.off();
```

```
   Particle.publish("Still online", "Cycle complete", 60, PRIVATE);
}

void resetValues(){
  beatCount = 0;
}

void checkPeak() {
  int peak = 0;
  int maxDiff = 0;
  for (int i = 0; i < 10; i++) {
    if (maxDiff < values[i] - values[i + 10]) {
      maxDiff =  values[i] - values[i + 10];
      peak = i;
    }
  }
  beats[beatCount] = milliVals[peak];
  timer = millis();
  beatCount++;
  Serial.println(beatCount);
  if(led) digitalWrite(D7, LOW);
  else digitalWrite(D7, HIGH);
  led = !led;
}

float getVariabilityRMS() {
  float prev = 0;
  float avg = 0.0;
  int count = 0;
  short faultCount = 0;
  short average = averageBeat();
  for (int i = 3; i < BEATCOUNT; i++) {
    if (beats[i] - beats[i - 1] < average * LOWERBOUND) {
      i++;
    }
    else if (beats[i] - beats[i - 1] > average * UPPERBOUND) {
    }
    else {
      float l = (float)(beats[i] - beats[i - 1]);
      if(l > UPPERTIMEOUT && l < LOWERTIMEOUT && prev != 0) {
        avg += pow(l - prev, 2);
        prev = l;
        count++;
      }
      else if(l > UPPERTIMEOUT && l < LOWERTIMEOUT && prev == 0){
        prev = l;
      }
    }
  }
  avg = avg / count;
  avg = sqrt(avg);
  return avg;
}

short averageBeat() {
  return (60000 / getPreBPM());
}

short getBPM() {
  int count = 1;
  short BPM = 0;
  short average = averageBeat();
  while (count < BEATCOUNT && beats[count] - beats[0] <= 60000) {
    if (beats[count] - beats[count - 1] < average * LOWERBOUND) {
    }
    else if (beats[count] - beats[count - 1] > average * UPPERBOUND) {
      //Throw Warning?
      BPM += (beats[count] - beats[count - 1]) / getTime(count);
    }
    else {
      BPM++;
    }
    count++;
```

```
  }
  if (beats[count - 1] - beats[0] < 60000) {
    float mult = 60000.0 / (beats[count - 1] - beats[0]);
    BPM = BPM * mult;
  }
  return BPM;
}

short getPreBPM() {
  int count = 1;
  short BPM = 0;
  while (count < BEATCOUNT && beats[count] - beats[0] <= 60000) {
    if (beats[count] - beats[count - 1] > LOWERTIMEOUT) {
      BPM += (beats[count] - beats[count - 1]) / getTime(count);
    }
    BPM++;
    count++;
  }
  if (beats[count - 1] - beats[0] < 60000) {
    float mult = 60000.0 / (beats[count - 1] - beats[0]);
    BPM = BPM * mult;
  }
  return BPM;
}

short getTime(short i) {
  if (i > 0) {
    if (beats[i] - beats[i - 1] > LOWERTIMEOUT) {
      return getTime(i - 1);
    }
    else return beats[i] - beats[i - 1];
  }
  else return 0;
}

void moveVals() {
  for (int i = 0; i < 19; i++) {
    values[i] = values[i + 1];
  }
}
void moveMillis() {
  for (int i = 0; i < 19; i++) {
    milliVals[i] = milliVals[i + 1];
  }
}
```

Appendix B – Consent form

Study administrator is: ________________________________

Participant is: ________________________________

Participant number: ________________________________

This is a study about the evaluation of a smart system used for monitoring basic human function (Heart Rate, Heart Rate Variability & Activity). Our goal is to improve the quality of the rehabilitation process of elderly patients after a hip fracture. Your participation will help us achieve this goal.

In this session you will be using a working prototype and a reference measurement system. These systems will monitor the above mentioned artifacts for the duration of the test, approximately 10 minutes. After this you will be asked to fill out a questionnaire about your experience. A facilitator will stay near you and help you if problems may arise or you have questions.

All information collected in the session belongs to the research group and will be used for internal purposes. We will not videotape or audiotape the session. We may publish our results from this and other sessions in our reports, but all such reports will be confidential and will not include your name.

This is a test of the system. We are not testing you. We want to test the functionality of the system and find out what aspects are confusing, so we can make it better. You may stop your participation in the study at any time.

Statement of Informed Consent

I have read the description of the study and of my rights as a participant. I voluntarily agree to participate in the study.

Print Name: ________________________________

Signature: ________________________________

Date: ________________________________

Appendix C – System User Score (SUS) Questionnaire

I think that I would like to use this system frequently

1	2	3	4	5
Don't agree				**Strongly agree**
o	o	o	o	o

I found this system unnecessarily complex

1	2	3	4	5
o	o	o	o	o

I thought the system was easy to use

1	2	3	4	5
o	o	o	o	o

I think that I would need the support of a technical person to use the system

1	2	3	4	5
o	o	o	o	o

I found the various functions in this system were well integrated

1	2	3	4	5
o	o	o	o	o

I thought there was too much inconsistency in the system

1	2	3	4	5
o	o	o	o	o

I would imagine that most people would learn to use this system very quickly

1	2	3	4	5
o	o	o	o	o

I found the system very cumbersome to use

1	2	3	4	5
o	o	o	o	o

I felt very confident using the system

1	2	3	4	5
o	o	o	o	o

I needed to learn a lot of things before I could get going with this system

1	2	3	4	5
o	o	o	o	o

Appendix D – Test Results

Test 1 (m, 21):

Time	Glasses	Zephyr	Zephyr average	HRV Glasses	HRV Zephyr (avg)	Diff (G-Z)	Diff %
15:58:26	61	64	70	78	84	-6	0,07142857
15:58:58	70	71	65	72	85	-13	0,15294118
15:59:32	65	63	65	73	85	-12	0,14117647
16:00:20	66	69	67	52	80	-28	0,35
16:01:18	59	61	68	83	83	0	0
16:02:00	65	66	67	58	80	-22	0,275
16:03:00	67	70	67	87	78	9	0,11538462
16:04:09	53	69	70	87	76	11	0,14473684
16:05:21	64	70	69	63	76	-13	0,17105263
16:06:29	64	70	76	63	72	-9	0,125
16:07:39	64	74	71	63	74	-11	0,14864865
16:08:50	64	67	68	63	73	-10	0,1369863
16:09:25	59	64	65	90	77	13	0,16883117
16:10:08	76	76	70	99	82	17	0,20731707

Test 2 (m, 21):

Time	Glasses	Zephyr	Zephyr average	HRV Glasses	HRV Zephyr (avg)	Steps Glasses	Skagen SW
17:08:36	71	66	75	55	69	11	
17:09:09	67	64	65	46	69	0	
17:09:40	67	64	66	100	69	29	
17:10:11	64	62	63	112	69	19	
17:10:41	78	83	74	86	69	19	
17:11:11	70	81	82	91	69	29	
17:11:53	70	68	73	101	69	24	
17:12:20	70	84	72	96	116	45	
17:12:47	81	99	93	60	119	29	
17:13:25	63	113	106	35	119	55	
17:13:49	67	115	117	243	119	77	
17:14:12	50	127	124	38	119	61	
					Total:	398	316

Test 3 (m, 22):

Time	Glasses	Zephyr	Zephyr average	HRV Glasses	HRV Zephyr (avg)	Diff (G-Z)	Diff %	Steps Glasses	Skagen SW
15:24:18	77	86	75	76	97	-21	0,21649485	12	
15:24:48	73	96	80	134	103	31	0,30097087	8	
15:25:19	72	68	76	58	99	-41	0,41414141	0	
15:25:50	68	66	67	69	100	-31	0,31	0	
15:26:24	69	67	68	84	104	-20	0,19230769	0	
15:26:58	66	62	62	78	107	-29	0,27102804	0	

15:27:38	62	61	63	90	109	-19	0,17431193	0	
15:28:26	59	63	65	86	110	-24	0,21818182	0	
15:29:06	58	61	61	75	79	-4	0,05063291	0	
15:30:08	65	67	66	72	70	2	0,02857143	0	
15:31:18	65	66	66	72	72	0	0	0	
15:32:04	67	68	68	80	74	6	0,08108108	0	
15:32:38	65	64	61	66	73	-7	0,09589041	0	
15:33:09	69	68	66	60	69	-9	0,13043478	0	
15:33:40	71	73	68	64	70	-6	0,08571429	0	
15:34:10	69	70	73	55	72	-17	0,23611111	0	
15:34:41	69	67	67	54	74	-20	0,27027027	0	
15:35:12	72	91	71	90	103	-13	0,12621359	1	
15:35:37	78	92	94	65	118	-53	0,44915254	21	
15:36:07	79	81	86	67	120	-53	0,44166667	18	
15:36:34	79	85	84	60	108	-48	0,44444444	16	
15:37:02	77	70	80	64	105	-41	0,39047619	15	
15:37:33	69	68	74	116	107	9	0,08411215	12	
15:38:03	72	91	74	86	107	-21	0,19626168	10	
15:38:33	72	84	77	58	98	-40	0,40816327	0	
15:39:02	74	85	81	77	86	-9	0,10465116	9	
15:39:31	77	83	78	72	80	-8	0,1	15	
15:40:02	72	78	74	55	77	-22	0,28571429	17	
15:40:44	75	77	75	72	74	-2	0,02702703	16	
15:41:09	78	81	78	67	66	1	0,01515152	2	
15:41:55	70	81	74	71	56	15	0,26785714	13	
15:42:31	71	82	74	69	52	17	0,32692308	15	
15:43:10	72	74	73	67	51	16	0,31372549	4	
15:43:44	66	83	76	51	51	0	0	1	
15:44:13	75	83	76	92	72	20	0,27777778	0	
							Total:	205	168