Development of an HRV Biofeedback Tool for signalling Anxiety Levels to Female Competitive Track and Field Athletes

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Abstract

Females competing in individual sports are the group that experience the highest levels of competitive anxiety, which is the physiological factor that has the biggest influence on sports performance. A link had been found between heart rate variability (HRV) and anxiety. HRV biofeedback has found to be a promising intervention for reducing anxiety. Therefore, this project looked into the development of an HRV biofeedback tool to signal anxiety levels to female, competitive track & field athletes. This project provides a detailed overview on the factors that are needed to develop an HRV biofeedback tool. These factors include heart rate data acquisition and filtering, HRV measure determination and feedback determination and realisation. The most important conclusion is that the heart rate data to be acquired must cover the entire heart rate spectrum from minimum to maximum. Besides that, the calculation of time intervals between consecutive heart rate peaks must be possible, from which HRV measures can be derived. Finally, since the tool is to be used during sports movements, the measuring device must be able to handle EMG noise from muscle artifacts and preferably be wireless to allow for ease of wearing. Root mean square standard deviation (RMSSD) proves to be most accurate HRV measure for short-term measurements of 30 seconds when compared to the standard measurement time of 5 minutes for HRV determination.

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Chapter 1- Introduction

Competitive anxiety is a type of anxiety which athletes experience before or during competitions [1] and is the physiological factor that has the biggest influence on sport performance [2]. Competitive anxiety is dependent on gender, type of sport and age. The group that shows the highest levels of anxiety is females performing in individual sports. In general, female athletes appear to experience feeling anxious more often than male athletes [3] and athletes from individual sports have been found to report higher scores of anxiety in comparison to athletes in team sports [4]. A possible explanation for this is that the pressure to achieve a desired outcome is dependent on the individual alone, which intensifies the anxiety symptoms.

The influence of anxiety on sport performance varies largely between athletes. Athletes can experience competitive anxiety as negative, positive or neutral to their performance. For every athlete individually, their best performance is experienced when their anxiety levels are within a set range on a low to high scale of anxiety levels, called the athlete's Individual Zone of Optimal Functioning [5].

Competitive anxiety is usually determined though observations and questionnaires. One of the most frequently used tools is the Sport Anxiety Scale-2 [6]. Even though these methods seem to work well for determining the anxiety levels in athletes, they do not provide the athlete with direct feedback on their anxiety levels.

A relationship has been found between anxiety and heart rate variability (HRV), which describes the time variation between consecutive heart rate peaks [7]. Positive and negative emotions can be distinguished by observing changes in heart-rhythm patterns, which become more erratic and disordered during the experience of negative emotions such as anxiety [8]. The effect of HRV biofeedback on sports performance has been investigated amongst male and female basketball players at university level and above, where evidence was found which supports the idea that HRV biofeedback lowers anxiety, showing a potential association between HRV biofeedback and performance optimization. [9]

Competitive anxiety and HRV both vary largely between individuals depending on gender, age and type of sport, which creates both a challenge in and a reason for developing a system to determine anxiety levels from biodata in a specific group. This research therefore aims at developing an HRV biofeedback tool that provides competitive female track and field athletes with real-time feedback on their anxiety levels.

1.1- Research question

Research question: How to develop an HRV biofeedback tool to signal anxiety levels to female competitive track & field athletes?

Sub-questions:

- What type of feedback modality is suited for the environment in which the HRV biofeedback tool is meant to be used?
- To what extend is it possible to provide the athlete with real-time feedback during a competition/training?

Chapter 2- Background research

This chapter covers the background research for this project. First, terms *competitive anxiety* and *heart rate variability* defined and the relation between anxiety and heart rate variability (HRV) is discussed. After this, the term *biofeedback* is introduced and state of the art examples for HRV biofeedback are provided. To complete the background research, devices for measuring HRV are discussed, as well as aspects of feedback in sports environments and the rules of the sport that serves as the environment for this project.

2.1- Competitive anxiety

Competitive anxiety is defined as the sport-specific trait anxiety that regularly appears before or during competitions [1]. This type of anxiety is split up into two components- somatic and cognitive anxiety. The somatic component refers to the reactions in the body of the athlete that they may experience before and/or during participation in sports competitions, for example elevated heart rate, muscle tension, stomach problems and hand tremors. The cognitive component relates to the problems with concentration and effective thinking, as well as anxiety about how to successfully cope with athletic competition [6]. Due to the growing demand, multiple scales have been developed for accurate and reliable diagnosis of sports anxiety. Scales that are frequently used include: Sport Competition Anxiety Test (SCAT), Competitive State Anxiety Inventory (CSAI-2 and CSAI-2R) and Sport Anxiety Scale (SAS and SAS-2). Due to its high validity and reliability indices, as well as the potential ease and speed of taking the survey, the Sport Anxiety Scale-2 (SAS-2) is one of the most widely used tools. [6]

According to literature, anxiety does not always have a negative impact on sports performance [6]. The concept of "directionality of anxiety" was introduced, where the assumption is made that the competence to interpret anxiety symptoms is impacted by the human ability to control the stressors. The interpretation and influence of anxiety on sport varies largely between athletes, who can experience competitive anxiety as negative, positive or neutral to their performance. Every athlete possesses an optimal range of anxiety that is most beneficial for their performance, which is known as an athlete's Individual Zone of Optimal Functioning (IZOF) [5], of which an illustration can be found in Figure 1: Illustration of athletes' IZOF. One athlete performs best when their anxiety level is in the lower ranges, where the performance of another athlete is the best when their anxiety level is in the higher ranges. Human interpretation of anxiety symptoms is determined by multiple factors including self-confidence, personality traits, coping strategies, cognitive abilities, sports level and situational factors [6].
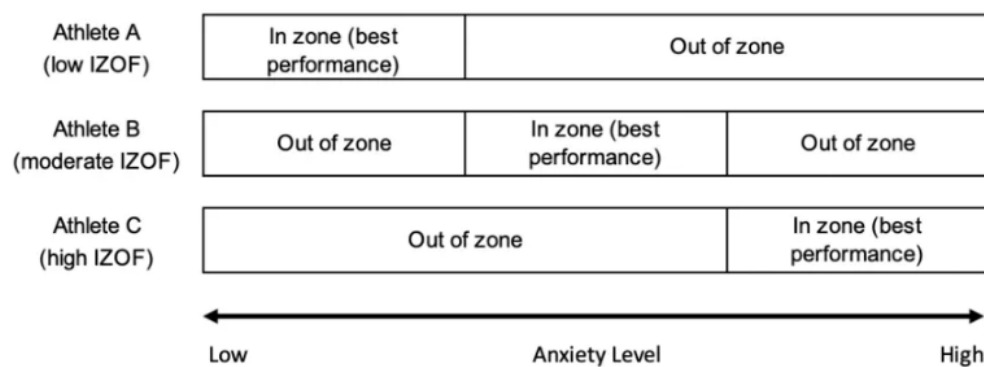
Figure 1: Illustration of athletes' IZOF

Research has shown competitive anxiety to be dependent on gender, type of sport and age. Female athletes appear to be more prone to feel anxious than male athletes [3]. Female athletes show higher levels of competitive trait anxiety [10], whereas males indicated greater concentration disruption [11]. These findings are agreed on by previous studies regarding gender effects on competitive anxiety [12], but disagree with other studies [13]. Research looking at anxiety levels in comparison to the type of sport has found varying conclusions, but generally, athletes from individual sports seem to experience more anxiety. One study [4] has found athletes from individual sports to have reported significantly higher values of general sport anxiety. This is in line with other studies, in which researchers claim to have found athletes from individual sports to report higher scores of cognitive anxiety, somatic anxiety and worry in comparison to athletes in team sports [4]. One explanation given in literature on the cause of higher competitive anxiety in athletes from individual sport is that the pressure to achieve a desired outcome will be borne by the individual alone, which intensifies the anxiety symptoms [1]. One study showed the worry scale to demonstrate a contradictory result to the other anxiety subscales, where team sports presented a significantly higher value than individual sports [6]. There are also studies, however, that have found no significant influence of type of sport on competitive anxiety [13]. Competitive anxiety is also found to be dependent on the age of the athlete. Older athletes experience higher levels of cognitive anxiety [14], however, research has also shown these older athletes to exhibit better coping strategies and being more likely to perceive this type of anxiety as facilitating to their performance [4] [14].

2.2- Relation between heart rate variability and anxiety

Research has shown that positive and negative emotions can be distinguished by observing changes in heart rhythms patterns, which become more erratic or disordered during the experience of negative emotions such as anxiety. [8] Heart rate variability (HRV) is a heart rate (HR) attribute defined as a measure of the variation in duration between each heartbeat over time [7]. This measure can be derived by integrating over the high frequency spectral component of R-R intervals at 0.15-0.40 Hz [15]. Faster HRs reduce the time between successive beats and therefore the opportunity for the interbeat intervals (IBIs) to vary, which lowers HRV. Conversely, slower HRs increase the time between adjacent heartbeats and the chance for IBIs to vary, which raises HRV. This phenomenon is called cycle length dependence.

In a meta-analysis of 296,247 healthy participants, 50 HRV measures were examined. Women showed higher mean HR, potentially leading to a lower HRV. [16] Low HRV has been associated with a number of psychopathological states, including anxiety. High resting HRV has been shown to predict self-regulatory strength and reduced negative emotion during acute stress. [15] Reduction of HRV can happen before situations that generate stress and anxiety in a subject, for example during competition events [7]. When working with HRV, measurement context on baseline HRV values such as recording period length, subject age and sex are highly important due to their varying impact on the HRV [16].

2.3- HRV biofeedback

Biofeedback is defined as: "*the process of measuring various normal physiological parameters and visualizing these measurements in real time, to increase a subject's awareness of the effect of their actions, thoughts and emotions can cause on their organism, in order to develop greater control of these physiological parameters*" [7].

Research has found HRV biofeedback to be a highly promising intervention for reducing anxiety and stress in general. The attractiveness of this intervention as a treatment aid is increasing with the rapid improvements and affordability of wearable devices such as fitness trackers and smart

watches. [15] Biofeedback training has demonstrated some positive psychological effects specifically in sport performance such as the reduction of anxiety. Effects assessed in a group of healthy male athletes revealed significantly positive effects on self-report measures of anxiety and stress. [8]

Commonly used interventions aimed at reducing stress and anxiety include techniques such as progressive muscle relaxation, listening to relaxing and classical music, cognitive-behavioural interventions and meditation [8].

2.3.1- State of the Art 1

One example of an HRV biofeedback intervention created to reduce anxiety is ViBreathe [17]. This is a tool developed to reduce anxiety in office workers via the use tactile feedback. Although this tool is aimed at office workers and not female track and field athletes, it is still interesting to look into the tool itself, of which a breakout of its components can be seen in Figure 2: Breakout of the components inside of the ViBreathe tool. Next to this, this tool provides useful insight in how HRV is used to provide biofeedback. The last point of interest from this tool for this research is the interaction with the user. This biofeedback tool provides tactile feedback to the user in the form of vibrations that guide the user's breathing rhythm. HRV is calculated via a peak detection algorithm over a blood volume pulse (BPV) signal, measured with a photoplethysmography (PPG) sensor. The personal HRV range of the user is measured beforehand via two steps: normal breathing for a minute, following by one minute of taking deep breaths as slowly as possible. During the first measurement, the minimum HRV is calculated, during the slow breathing, the maximum HRV is calculated, which together form the personal HRV range. This method for calculating the personal HRV range does not seems to be scientifically approved, but does provide useful insight into how HRV can be used to provide biofeedback, since values of HRV vary largely between individuals. The ViBreathe tool provides three guidance modes: standard, responsive and adaptive. The first two modes use a fixed breathing guidance pace. In the adaptive guidance mode, the breathing pace is adjusted in real-time using the user's short-term HRV. Although users experienced this type of feedback as easy to understand and effortless to perform the biofeedback training with, its simple and non-reactive behaviour caused some of the users to feel bored or sleepy after using it for a while.
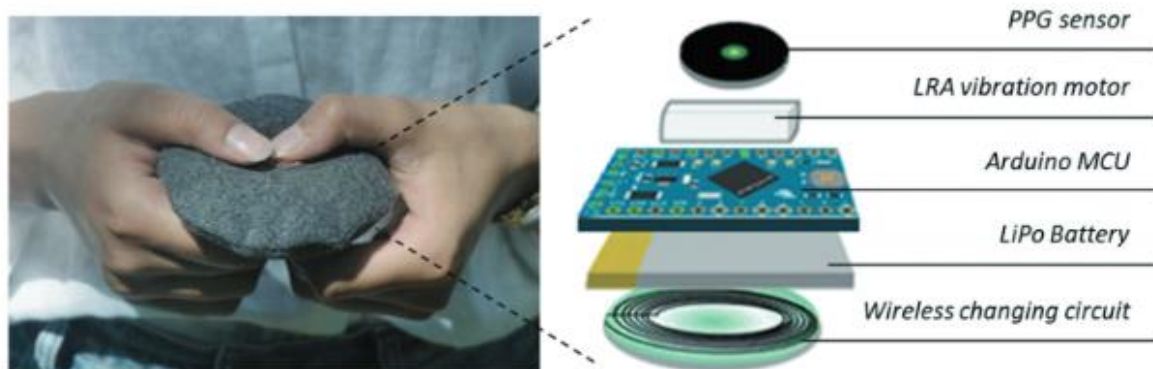
Figure 2: Breakout of the components inside of the ViBreathe tool

2.3.2- State of the Art 2

A second example of an existing HRV biofeedback comes from a Dutch TV show called *"Klaas kan alles"*. This TV show has done an episode on stress levels, in which the host used an app that provided biofeedback on his stress levels [18]. These stress levels were determined via HRV and the host used show breathing techniques to try and influence his HRV and with that stress levels in a very stressful situation, hanging 220 meters above the ground. Even though his stress levels were initially extremely high during this stressful experience, he eventually managed to lower his anxiety levels to a normal level. The application providing him with this biofeedback is shown in Figure 3. It shows a meter with two colours, blue and orange. Higher stress levels caused the indicator to indicate a level in the orange zone, where lower stress levels were indicated in the blue area.
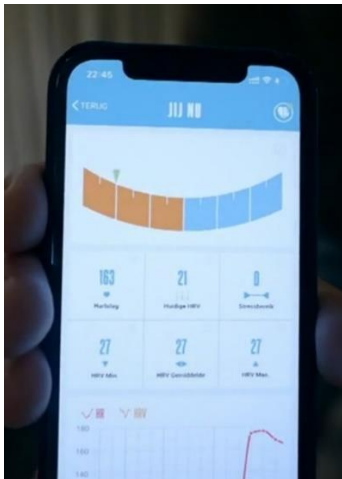
Figure 3: Feedback application used in "Klaas kan alles" episode

2.3.3- State of the Art 3

Another example of existing HRV biofeedback on stress is the visual HRV biofeedback which smartwatches from brand such as Garmin provide [19]. Both on the watch and in the accompanied Garmin Connect app, an visual overview is provided on the user's stress levels. How this biofeedback looks on a Garmin watch and in the Garmin Connect app is shown in Figure 4 and Figure 5.

Figure 4: Visual biofeedback on stress levels on Garmin watch
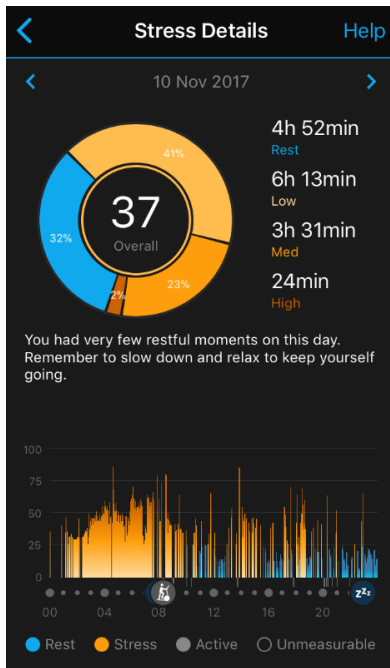
Figure 5: Visual feedback on stress levels in Garmin Connect app

2.3.4- State of the Art 4

Another way in which anxiety is currently being displayed is described in an article on anxiety level recognition for a virtual reality therapy system using physiological signals [20]. Anxiety levels are displayed here visually using an image of a thermometer, divided in different coloured sections labelled with the accompanying anxiety level. This visualization of anxiety levels can be seen in Figure 6.
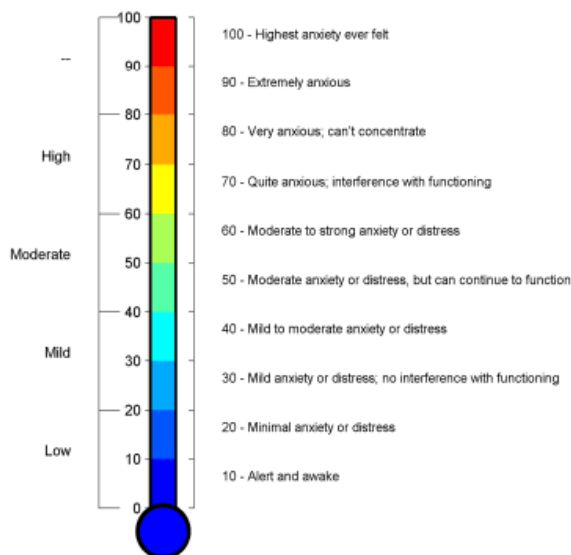
Figure 6: Visualization of anxiety levels displayed on a thermometer shape

All three visible tools (the application from the TV show "Klaas kan alles", both of the Garmin stress overviews and the anxiety thermometer) use colours to indicate the intensity of the stress and anxiety levels. High levels are indicated by shades of orange and red, shades of blue indicate lower levels, or a state of rest. If this research decides to go for a visual HRV biofeedback tool, taking into account the meaning of these colours may be useful.

2.3.5- State of the art 5

The final state of the art for this project is a project that is very related to this project. It regards the project done by Dennis Peeters regarding the communication of real-time emotional states through data physicalizations [21]. This work investigated the challenges and opportunities involved in physicalizing emotional data derived from biosignals in real-time.

2.4- Devices for measuring HRV

Deriving HR attributes as HRV from (raw) data is not the goal of this research, which means that finding a device that does this already is ideal. From a literature review on wrist- and chest worn devices for measuring heart rate data [22], follows that chest-bands are the most accurate of the two wearables, reaching accuracy percentages of 99% when compared to ECG measurements. From the devices reviewed, the Polar brand chest band proved to be the most accurate. Reviewed brands included amongst others Apple, Polar, Garmin and Fitbit.

After further research, it was concluded that a different brand is commercially available that directly provides HR attributes amongst which the most important one, HRV. The brand Zephyr offers several devices for very accurately measuring heart rate data and has patented algorithms which allow for in-depth HR-derived analysis including HRV information [23], which is something that the brands previously reviewed do not offer to the same extend.

2.5- Aspects of feedback in sports environments

Properties of feedback

Feedback in sports environments serves a few main purposes. Firstly to raise the athlete's awareness, secondly to guide the athlete's intentions and actions and lastly to reinforce behaviours [24]. Properties of feedback are split up into five relevant categories for the design of a feedback tool: timing, modality, frequency, content and function of the feedback [25]. The different modalities of feedback relevant for this research will be explained in the following section.

Modalities of feedback

Extrinsic feedback is often delivered through visual, auditory or tactile feedback, where the coach plays a crucial role in providing direct feedback through demonstrations or verbal explanations [24].

Visual feedback ranges from realistic representations to increasingly abstract mappings and visualisations. It can be used to provide instructions and embellishments as well as direct feedback on an athlete's performance. Although visual displays allow for the delivery of complex information, this may not always be desirable. Simpler displays that only show relevant parts of a movement for example are sometimes chosen deliberately. [25]

Auditory feedback uses the many properties of sounds, such as pitch, timbre, rhythm, etc, to deliver feedback information to the user. This feedback can be in the form of simple sounds when a certain threshold value is exceeded, but also by directly mapping measurement values to sound parameters. The amount of dimensions of sound allow for higher order data to be characterised by sounds. Research has shown certain measures to be best captured by specific dimensions. For example, it is found that information about timing is best captured by rhythmic patterning of a pitch-mapped stream and information about key events is best communicated through changes in loudness. [25]

The last modality of feedback relevant for this research is tactile feedback, which refers to any information a user gets from contact or touch [24]. Similar to auditory feedback, tactile feedback

provides a range of dimensions to be utilised for communicating information, including the number and placement of actuators, frequency, intensity and (relative) rhythmic patterning [25].

Next to visible, auditive and tactile feedback systems, multimodal systems can be developed, which create a more immersive experience by allowing more information to be communicated. Various combinations of multimodal systems have been explored previously: audio-visual, audio-tactile, tactile-visual and audio-visual-tactile. The risk of using multimodal systems is that people can feel overwhelmed when presented with too much information. A lot of work still has to be done to understand which systems work well under which circumstances, due to the immense amount of degrees of freedom. [25]

2.6- Rules of track and field regarding data measuring and communication devices

Since this research aims at developing an HRV biofeedback tool to determine anxiety levels in female track and field athletes, it is necessary to take into account any rules from the sports federation which may provide restrictions for the development of the tool. The world-wide federation of track and field is called World Athletics. Their website provides an elaborate section on the Constitution and the Rules and Regulations of World Athletics. The rules relevant for this research are mentioned in the following section and are taken from the World Athletics Book of Rules [26].

Assistance not allowed

Rule 6.3.2- Possession or use of video recorders, radios, CD, radio transmitters, mobile phone or similar devices in the competition area.

Assistance allowed

Rule 6.4.1- Communication between the athletes and their coaches not placed in the competition area.

Rule 6.4.4- Heart rate or speed distance monitors or stride sensors or similar devices carried or worn personally by athletes during an event, provided that such device cannot be used to communicate with any other person.

An important note to add is that these rules apply only during the actual participation in a competition event, meaning that they do not need to be obeyed during all other times, including the preparation and warming-up phase before a competition takes place, the time in between participation in different events of the same competition, or during training hours.

2.7- Discussion + conclusions

From this background research, we can draw several conclusions. First of all, it is concluded that the group showing the highest levels of competitive anxiety are females performing in individual sports. This could be explained by the facts that females tend to have higher heart rates and therefore a lower heart rate variability, which has shown to be a measure of anxiety. People performing in individual sports tend to experience higher anxiety levels because the pressure to achieve a desired outcome is borne by the individual alone, which intensifies anxiety symptoms.

HRV biofeedback has been found to be a promising intervention for reducing anxiety. Multiple examples are provided as state of the art, which use colours to visualize emotions. To determine the modality of the feedback, the sports environment is investigated from which the rules must be obeyed. The information gained from the background research serves as a base for the rest of the research.

Chapter 3- Methods and Techniques

This chapter discusses the methods and techniques used in the project. It contains the Creative Technology design process, within which multiple methods and techniques are used to complete this project.

3.1- Create design process

The Creative Technology design process serves as a base for this research. It describes four phases which built up the development phase of a research. These four phases include: ideation, specification, realisation and evaluation. Within each of these phases, methods and techniques exist to complete that phase and prepare for the next phase.

3.1.1- Ideation

Stakeholder identification

The term "stakeholder" is defined and stakeholders and their role in the research are described.

Stakeholder analysis

The stakeholders are analysed via two methods to determine stakeholder and user needs. The first method used is interviews. An unstructured interview is held with two target users, both female competitive track and field athletes, to get a first feeling about their needs to serve as a base for the user needs. Another unstructured interview is held with one of the supervisors of the project, to determine the needs for this project from the side of the researcher. Additionally, first-person method will be used by the researcher doing this project to further determine user needs.

First person research methods [27]

"First-person methods are qualitative research approaches that turn to the researcher as the subject of inquiry. The insights rely on the researcher's own first-hand experience of a phenomenon as the starting point of knowledge production."

"A third-person point of view to systems implies designing for society in general; a second-person point of view implies designing with a group of people part of society; and a first-person point of view implies designing for yourself within the society and proposed system."

"In first-person research, the line between the personal and the professional gets blurred. Our opinion, point of view, decisions, and mistakes can be seen as a valuable starting point for learning."

Stakeholder needs including prioritization

Using the MuSCoW method [28], a list is created of stakeholder and user needs, following from the stakeholder analysis. This technique prioritizes requirements in the following categories: must have, should have, could have and wish.

Classification of (preliminary) requirements

The preliminary requirements are formed by combining the stakeholder and user needs and classifying them using the MuSCoW method.

Generating preliminary concepts

Preliminary concepts are based on the preliminary requirements. A list of objects that the potential user brings with them to the location where the tool is meant to be used is created to serve as a base for the concepts. The concepts are either additions to the objects that are already present, or other

objects that are portable and easy to take with. Other preliminary requirements are taken into consideration and added to the tool as much as possible. Preliminary concepts are sketched on a tablet and described in the context in which they would potentially be used.

Determining final concept

The final concept is determined by the researcher, who is also a potential user. The other stakeholders have mentioned in the stakeholder analysis not to have a preference for the design part of the tool, making it a fair choice to let the potential user determine which concept speaks to them the most. All preliminary concept have taken into consideration the requirements of all stakeholders and have tried to fulfil as many as possible.

3.1.2- Specification

Creating a persona

Personas are distilled essences of real users and are used in user experience (UX) design to build empathy with target users and focus on their world [29]. Because the researcher doing this project is also a potential user, the persona is based on their personal experiences as a female competitive track and field athlete. Context is provided to build this persona and their problem which the project aims to solve is described in context.

Creating an Interaction Scenario

An interaction scenario serves as a tool to describe the tool in its intended environment. Lots of details are added to create a specific situation, with the aim of being understandable for both potential users and people developing the tool.

Determining System Requirements

System requirements are described, split up into functional and non-functional requirements. The functional requirements describe what the system should do and the non-functional requirements describe how the system should do this.

Functional architecture

The functional architecture of the system is described in detail by creating levels. These levels range from level 0 to level n and go in depth into the functions of the system and describe the relations between these functions. The depth of the functional architecture, or the amount of levels, is determined by the complexity of the system.

3.1.3- Realisation

HR data collection

Heart rate data is measured to serve as input for the calculation of heart rate variability, which is our physical measure for anxiety level. The heart rate data is measured via ECG, with ECG electrodes place via the Einthoven method. Einthoven's triangle is formed by lead placement, the leads are placed on the right arm, left arm and left leg or foot. This placement is shown in Figure 7 and Figure 8. Three leads can be formed. Lead I is formed with a negative electrode on the right arm, going towards a positive electrode on the left arm. Lead II goes from a negative lead on the right arm to a positive lead on the left leg/foot. Lead III goes from the left arm to the left leg/foot, with a negative electrode on the left arm and a positive electrode on the left leg/foot.
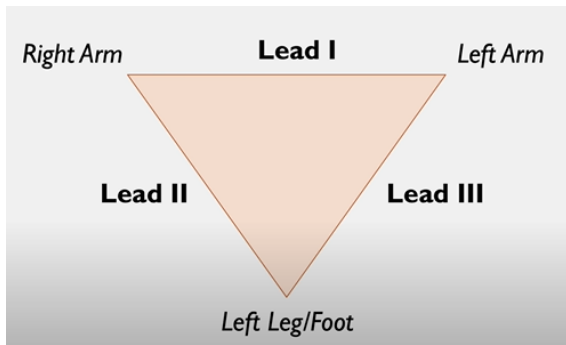
Figure 7: Einthoven's triangle

To determine the cardiac axis, we need to look at leads I, II and III. For normal cardiac axis, lead II has the most positive deflection compared to leads I and III. For right axis deviation, lead III had the most positive deflection and lead I should be negative. For left axis deviation, lead I has the most positive deflection and leads II and III are negative. The goal is to find the lead which provides the most positive deflection. This is the lead which we will be measuring and using to determine the HRV.
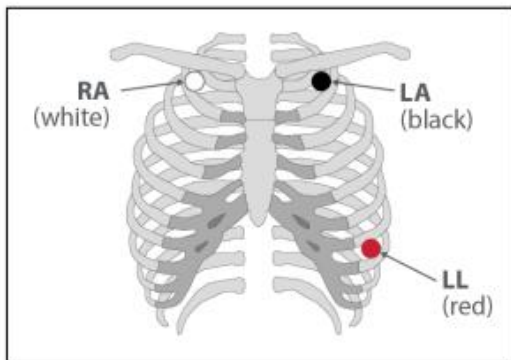
Figure 8: Measurement setup for lead II reading

Determining HRV data

HRV stands for heart rate variability, which is a measure of the time variation between consecutive heart rate peaks. A higher heart rate leads to a lower HRV which, according to literature, can indicate a higher anxiety level. An HRV measure needs to be chosen that is fitting to the goal of the project.

3.1.4- Evaluation

In the evaluation phase of the research, the functional prototype will be evaluated on with a user evaluation.

Chapter 4- Ideation

This chapter covers the ideation phase of the project. This includes a definition of the design question, stakeholder needs and requirements, as well as (preliminary) requirements and (preliminary) concepts. At the end of this chapter, a final concept is chosen and discussed in more detail.

4.1- Design question

This research aims at developing an HRV biofeedback tool that provides female competitive track and field athletes with real-time feedback on their anxiety levels.

4.2 Stakeholder needs and requirements definition

Stakeholder: Individual or organization having the right, share, claim or interest in a system or in its possession of characteristics that meet their needs and expectations

4.2.1 Stakeholder Identification

This section provides an overview of the stakeholders involved in this project. These include individuals, groups and organisations that are impacted by of invested in the project.

Data physicalization researcher

The first stakeholder in this project is the supervisor guiding the researcher through the project. They will take the role of the researcher and determine what the researcher aims to gain from this project.

Female competitive track and field athletes- potential users

The second stakeholders in this project are the potential users of the end product, female competitive track and field athletes. They play a crucial part in the design process of the project, as they provide important insights in the needs of the potential users of the tool and their opinions will be used to form a final concept. Additionally, they will be impacted by the project as well, because they are the potential users. The student doing the project falls into this category, being a female competitive track & field athlete.

World Athletics

The third stakeholder that needs to be mentioned is the global track and field federation "World Athletics". Their rules from the sport can potentially provide limitation for the final concept.

Companies

The final stakeholder that needs to be mentioned are companies who would want to make a commercial product out of this project. They potentially influence the requirements and design choices for the tool being developed.

4.2.2 Stakeholder Analysis

4.2.2.1 Supervisors of the project (Researcher role)

An interview was held with one of the supervisors of the project to determine stakeholder needs from the role as researcher. They mentioned some key points for the tool in terms of goal and design choices.

For the goal of the tool, there were a few key points. A first points of importance is that the tool must be a tool for self-reflection to help the athlete with anxiety. The researcher mentioned that research has been done on the impact of looking at visualizations on self-reflection. A positive effect was

found. They would like some more research to be done for the project into aesthetic experiences where self-reflection is used and their effects.

The design choices for the tool where left unspecified in terms of type of feedback and materials used. The researcher would like research to be done into which materials work best for this situation and other factors such as how to pick appropriate colours if colours are meant to be used. A paper is recommended to be read to serve as a tool for the design part: Introduction to the Special Issue on First-Person Methods in HCI.

Apart from that, one key point for the design is handiness or portability. They would like the tool to be easy to take with. Finally, they would like the tool to be something that does not interfere with the athletes doings, but does trigger interaction visually or another way. This balance between not interfering and still triggering interaction is a very interesting thing to research and has a lot of potential to be researched since the researcher doing this project is also a potential user and has a big network of potential users as well.

4.2.2.2 World Athletics
The rules from World Athletics which were previously mentioned in chapter 2 of this thesis provide some limitations in the ideation process of this project. Because possession or use of radio transmitters is not allowed by rule 6.3.2, it is not possible in this research to monitor the athlete's HR data during a competition via a Bluetooth connected device. Outside of competitions, these rules do not hold up, meaning that an HRV biofeedback tool that uses a Bluetooth connected device for data measuring can be developed to be used at all times by an athlete, with the exclusion of competitions.

4.2.2.2 User (expert) interview and expert opinions
An unstructured interview was held with two female competitive track and field athletes, who are potential users of the end product of the project. They are considered experts in this field. The interview was held with both females at the same time, in a casual setting.

First, a discussion was held on the moment during which competitive anxiety is experienced by them. Although this most likely varies between athletes, they both agreed on the same moment of the anxiety peak, namely right before competitions. To provide some context on the process before track and field competitions: after the athlete is done performing their warm-up, they enter a room called the "*call-room*". This is a room which they need to enter a set amount of time before the competition starts and where they have to wait until they are escorted by officials to the competition area, this waiting time is usually around 15-30 minutes. The call-room is an area where a lot of anxious tension tends to be present. Both athletes with which the interview was done mentioned this time to be the time during which they experience the most anxiety and where feedback on their anxiety may be the most beneficial.

Besides the athletes that were interviewed, the student performing this research project is also a potential user and therefore provides useful insight into the needs of the potential users. The interview with potential users focussed mostly on the timing of the feedback, but perhaps more important is the type of feedback. Needs regarding the type of feedback are not discussed with the athletes during the interview, but come solely from the researcher as potential user.

I, as researcher and potential user, agree with my fellow athletes that the call-room would be one of the most important moments for the feedback to be given. Because the call-room is a place where the athlete is usually sitting on a chair waiting, the options for a feedback tool in terms of shape and feedback form are quite large. Regarding shape of the feedback tool, something wireless that can either be worn or held by the athlete would be very practical. It would be optimal for the tool to not

be too heavy or bulky, as this would set the athlete up with a struggle of transporting the tool,. This could potentially cause them to be less inclined to use the tool, which must be avoided. Regarding the type of feedback, there are a few different options in general, with visual feedback, auditive feedback and tactile feedback being the most used ones. As one can imagine, auditive feedback would be the least practical of the three because it interferes the most with the surroundings of the athlete. The tool being a disturbance to other athletes is something that must be avoided. This could be avoided by providing auditive feedback via headphones, but is not ideal. This leaves two feasible options in terms of feedback type: visual and tactile feedback.

After this, a discussion was held on what kind of feedback they think would be beneficial for reducing competitive anxiety. Their opinions were that the main cause of the anxiety in the call-room is caused by the fact that the athlete needs to sit there and wait until the competition starts. To reduce this anxiety, they are of the opinion that it would be nice to have a tool that distracts them from waiting and focusses their mind on something else instead.

One last point that came up from these discussions is that although relaxation methods have shown to decrease anxiety, not all athletes want to get very relaxed, because for competing, some of them benefit from the tension and bodily responses that anxiety gives them. This is however not the case for all athletes, which makes the development of one tool that helps all athletes in this situation difficult.

4.2.3 Stakeholder needs
This section provides a complete list of stakeholder needs, including user requirements and stakeholder requirements, prioritized via the MuSCoW method. This method categorizes and prioritizes requirements in the following categories: must have, should have, could have, wish.

4.2.3.1 User requirements
The feedback tool must:

- measure data via a sensor in a way that does not bother the athlete or disrupt them during their competition preparation phase

The feedback tool should:

- provide either visual or tactile feedback
- provide feedback in a simple and intuitive way
- be able to provide feedback in the call-room

The feedback tool could:

- provide auditive feedback as long as this does not interrupt with the athlete's environment
- either be wearable or wireless to allow for easy transportation and use

Wish:

- Wish requirement

4.2.3.2 Stakeholder requirements
Data physicalization researcher

The feedback tool must:

- be a tool made for self-reflection
- be something that triggers interaction, actively capturing the user's attention to ensure use

- use annotated data in order to see how the physiological data links to perceived anxiety level
- include context data before the use of the system (sleep, tiredness, caffeine intake, alcohol intake, etc.)

The feedback tool should:

- allow the user to compare competition anxiety levels between X time ago and the day of the competition

The feedback tool could:

- focus on handiness or portability. It should be easy to bring along

Wish:

- for exploring different materials for the tool and thinking about the effects of colours for example
- base the design on the experience of potential users, no preference from the stakeholder regarding the design

World athletics

The world-wide track and field association World Athletics has a rulebook, as mentioned before. These rules provide limitations to the project and with that a few must-not-have's for the final concept. Important to mention is that these rules only apply during a track and field competition. Outside of a competition, there are no rules and therefore no boundaries relevant to the project.

The feedback tool must:

- not make use of a video recorder, radio, CD, radio transmitter, mobile phone or similar devices in the competition area
- use a heart-rate monitor worn personally by the athlete if the tool is used during a competition, provided that the monitoring device cannot be used to communicate with any other person

The feedback tool should:

- be designed in a way that its use does not interfere with other athletes than the one using it

4.2.3.3 Preliminary requirements
A set of requirements follows from the background research and stakeholder identification and analysis. These requirements are categorized into four categories via the MoSCoW method [28]: must have, should have, could have and wish.

The feedback tool must:

- not be used during the competition if it makes use of a video recorder, radio, CD, radio transmitter, mobile phone or similar device
- be a tool made for self-reflection
- be something that triggers interaction, actively capturing the user's attention to ensure use
- measure data via a sensor in a way that does not bother the athlete or disrupt them during their competition preparation phase

The feedback tool should:

- be designed in a way that its use does not interfere with other athletes than the one using it
- allow the user to compare competition anxiety levels between X time ago and the day of the competition
- provide either visual or tactile feedback
- provide feedback in a simple and intuitive way
- be able to provide feedback in the call-room

The feedback tool could:

- be wearable or wireless to ensure easy transportation and use. Focus on handiness and portability
- provide auditive feedback as long as this does not interrupt with the athlete's environment
- either be wearable or wireless to allow for easy transportation and use

Wish

- exploring different materials for the tool and thinking about the effects of colours for example
- base the design of the tool on the experience and needs of potential users, no preference from other stakeholders regarding the design

4.3 Preliminary concepts

This section provides five preliminary concepts that fulfil the preliminary requirements of section 4.2.3.3. For each concept, a scenario is added to analyse the operation of each concept in its intended environment.

4.3.1 Concept 1- Water bottle compartment with integrated LEDs

This concept consists of a compartment that can be added to a regular water bottle. The HRV is measured via a wireless heart-rate band. This compartment has LEDs integrated, which allow for visual feedback. As the LEDs light up under the water, the water appears to be coloured, highlighting the visual effect. There are three levels of feedback: green, orange and red. Green light indicated a calm state where anxiety levels are low. Orange light indicated an increased level of anxiety. Red indicates an anxious state, where anxiety levels are high.

Many athletes, if not all, carry water bottles with them during the warm-up and preparation phase of a competition. This means that this concept can be very nicely integrated with the objects that the athlete brings to a competition. If HRV is measured using a heart-rate band, this concept would fulfil the requirement of being wireless and easy to transport. Since a water bottle is already brought by the athlete, this concept should not provide a burden to the athlete.

Figure 9: Preliminary concept 1

Scenario

An athlete enters warm-up terrain before a competition. They start their warm-up by running and doing some exercises. During this time, it is important to keep drinking water to avoid dehydration. Before starting their warm-up, the athlete has set aside their water bottle within arm's reach to make sure they can take a sip as soon as they get thirsty.

During the beginning stages of the warm-up, the athlete is still quite calm and the water bottle is reflecting this by lighting up green. As the warm-up progresses and the competition gets closer, the athlete's heart rate starts rising and the bottle turns orange, indicating an increased HRV and with that increased anxiety levels. As the athlete needs to report in the call-room because the competition almost starts, the bottle turns red, indicating the highest levels of anxiety.

4.3.2 Concept 2- Bracelet with LEDs

Figure 10: Preliminary concept 2

The second concept is similar to the first in the way that the feedback is given. However, instead of a compartment beneath a water bottle, the LEDs are placed in a bracelet that can be worn by the user. The bracelet lights up in one of three ways, green, yellow or red, just like the water bottle compartment.

Scenario

An athlete enters warm-up terrain before a competition. They start their warm-up by running and doing some exercises. A water bottle and bag are usually within arm's reach during this time, but besides that, the athlete is moving a lot during warm-up exercises so other objects are not preferred during that time. Most athletes do wear a watch or other jewellery such as rings or bracelets for either practical purposes or personal preference.

One of the bracelets that the athlete is wearing had a practical purpose, it is a HRV feedback tool that provides the athlete with feedback on their anxiety levels during warm-up and the time leading up to a competition. During the warm-up the bracelet is lit up green, indicating that the athlete is in a calm state where low levels of anxiety are experienced. As the competition gets closer, the athlete starts to feel more anxious, which is indicated by the bracelet with orange coloured LEDs. When the athlete enters the call-room, anxiety levels peak because the competition is about to start and the bracelet lights up with a bright red colour. This creates awareness for the athlete and provides insight into their physiological data and its relation to competition anxiety.

4.3.3 Concept 3- Vibrating bracelet

The third concept uses the same idea of a wearable bracelet as the second concept, but provides tactile feedback instead of visual feedback. As a bracelet is wearable, the feedback can be given via vibrations on the wrist. This has the potential of being a more subtle way of feedback than a bracelet or water bottle that lights up. One vibration indicates a low anxiety level, or calm state. Two vibrations indicate that the anxiety level has increased and the athlete is in a more anxious state.
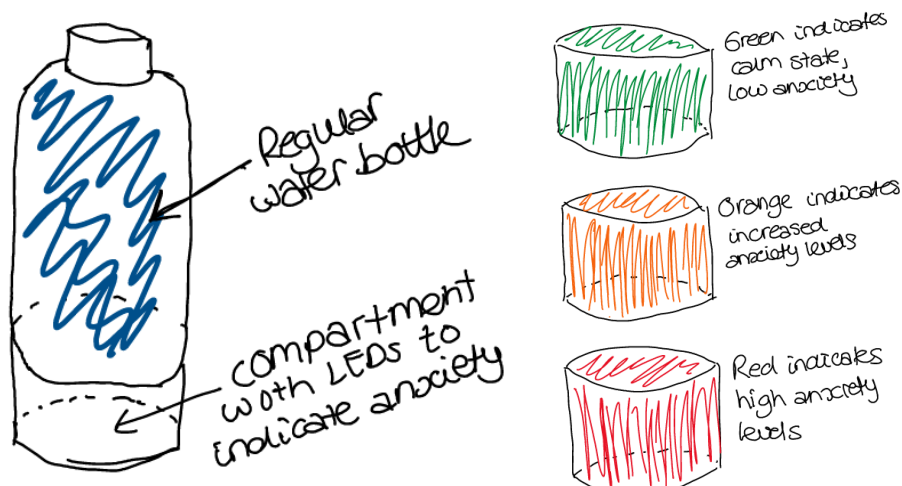

Figure 11: Preliminary concept 3

Scenario

An athlete enters warm-up terrain before a competition. They start their warm-up by running and doing some exercises. A water bottle and bag are usually within arm's reach during this time, but besides that, the athlete is moving a lot during warm-up exercises so other objects are not preferred during that time. Most athletes do wear a watch or other jewellery such as rings or bracelets for either practical purposes or personal preference. One of the bracelets that the athlete is wearing had a practical purpose, it is a HRV feedback tool that provides the athlete with feedback on their anxiety levels during warm-up and the time leading up to a competition. During the warm-up the bracelet, when the athlete is still quite calm, the bracelet does not give vibrations yet. When the athlete starts getting anxious, which is the tool picks up through measuring an increased HRV value, the bracelet gives two short vibrations, making the athlete aware of their raised anxiety levels. If the anxiety rises even more, two short vibrations are given again, notifying the athlete of this change. If the athlete focusses on becoming calmer again and succeeds in this, the bracelet provides feedback of lowered anxiety levels by giving one short vibration. This feedback system creates awareness for the athlete by providing insight into their physiological data and its relation to competition anxiety.

4.3.4 Concept 4- Add on for a shoe

The fourth concept consists of a small device that can be added to the shoe of the athlete. It is secured by tying the device to the shoelaces. The device contains LEDs that provide visual feedback, as well as vibrations to provide tactile feedback to the athlete on their anxiety levels. As with the previous concepts, a green LED represents a low level of anxiety, orange a medium and red the highest level of anxiety. When the anxiety rises and therefore the LEDs change colour, the athlete is also notified of this change via tactile feedback. An increasing change in anxiety levels is indicated by two short vibrations, a decreasing change in anxiety levels is indicated by one short vibration.
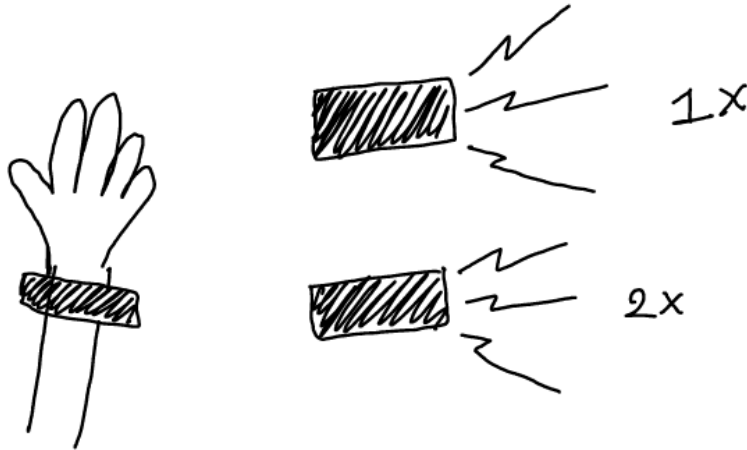

Figure 12: Preliminary concept 4

Scenario

An athlete enters warm-up terrain before a competition. They start their warm-up by running and doing some exercises. On the shoe of the athlete, a small device can be seen, attached to the shoelaces. This small device is a HRV feedback tool that provides the athlete with visual and tactile feedback on their anxiety levels during warm-up and the time leading up to a competition. During the warm-up the device is lit up green, indicating that the athlete is in a calm state where low levels of anxiety are experienced. As the competition gets closer, the athlete starts to feel more anxious, which is indicated by the device with orange coloured LEDs. The increase of anxiety levels is also indicated with two vibrations. When the athlete enters the call-room, anxiety levels peak because the competition is about to start and the device lights up with a bright red colour, accompanied by two vibrations once again, to indicate the rising of the anxiety levels. When the athlete gets calmer and anxiety levels decrease, the LEDs change colour again, and one vibration is given to indicate a change to a lower level anxiety. This system creates awareness for the athlete by providing insight into their physiological data and its relation to competition anxiety.

4.3.5 Concept 5- Smart watch application

The last concept consists of an app that displays information about the anxiety levels on the screen of a smart watch. A coloured stripe is visible behind the time on the smart watch screen, which indicated the anxiety levels of the athlete. As with the other concepts that use visual feedback, the colours red, orange and green are chosen to indicate high, medium and low anxiety levels respectively. Additionally, a notification is shown when entering the highest and lowest anxiety states. When entering the highest anxiety state, an exclamation mark is shown to signal that something it happening. When entering the lowest state of anxiety, a thumbs up is displayed to signal a positive change.
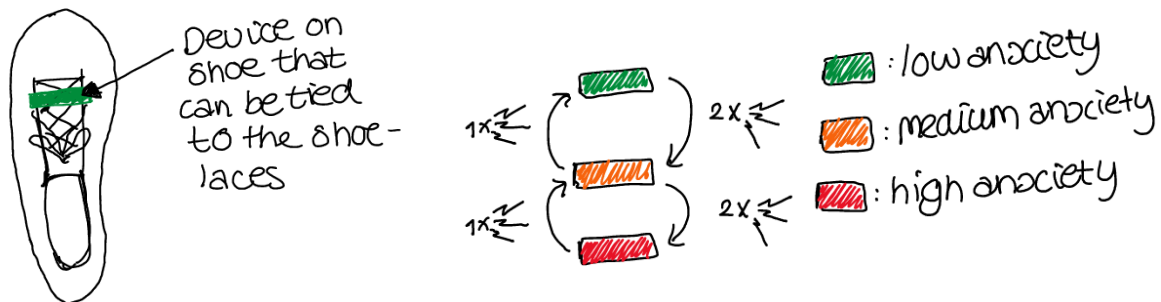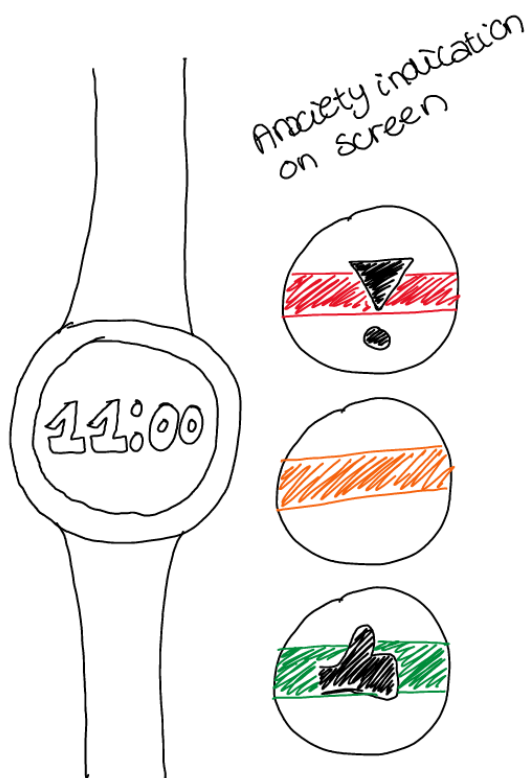

Figure 13: Preliminary concept 5

Scenario

An athlete enters warm-up terrain before a competition. They start their warm-up by running and doing some exercises. A water bottle and bag are usually within arm's reach during this time, but besides that, the athlete is moving a lot during warm-up exercises so other objects are not preferred during that time. Most athletes do wear a watch or other jewellery such as rings or bracelets for either practical purposes or personal preference.

The smart watch also serves as a HRV feedback tool that provides the athlete with feedback on their anxiety levels during warm-up and the time leading up to a competition. During the warm-up the screen shows a green bar, indicating that the athlete is in a calm state where low levels of anxiety are experienced. As the competition gets closer, the athlete starts to feel more anxious, which is indicated by on the screen of the watch with an orange coloured bar. When the athlete enters the call-room, anxiety levels peak because the competition is about to start and the watch screen shows a red bar. Additionally, the watch displays an exclamation mark when moving from the medium to the high anxiety state. This feedback creates awareness for the athlete by providing insight into their physiological data and its relation to competition anxiety.

4.4 Final concept

The final concept that is chosen is concept 1, the water bottle compartment with integrated LEDs. The choice for this concept as the final concept was made for two main reasons. Firstly, this concept can be integrated with an object that the potential user already takes with them to competitions. This means that the tool in this shape would not be a burden to bring along. Secondly, the way that this tool provides feedback with LEDs shining through the water feels more original than for example the bracelet concept with LEDs. Because this is a more unique concept, it potentially captures the user's attention better than a simpler concept.
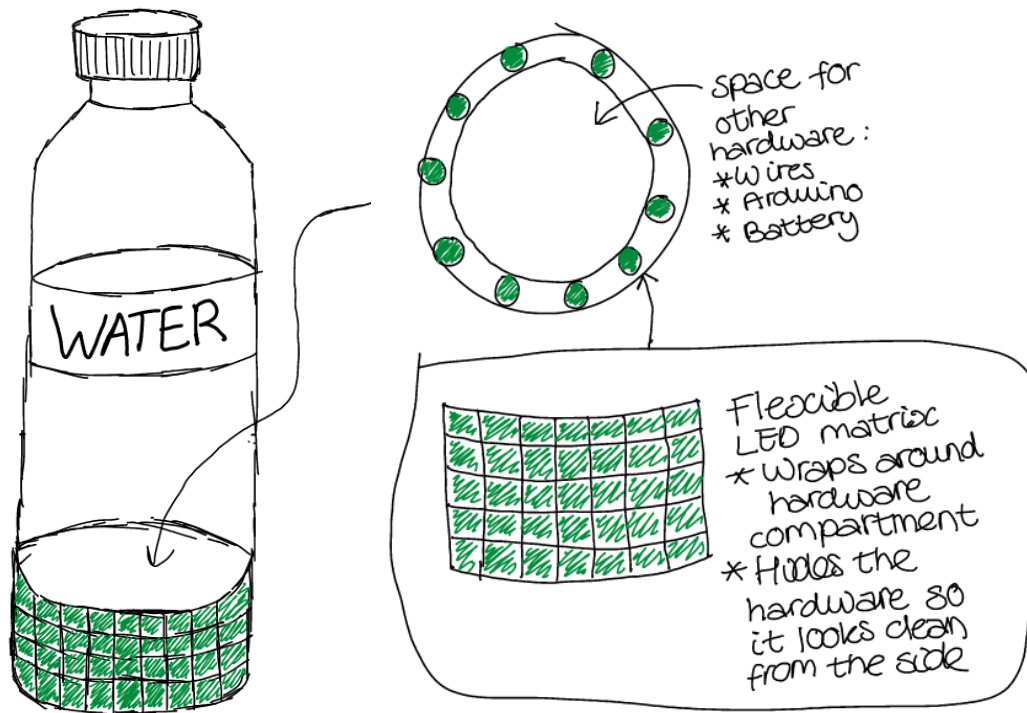
Figure 14: Final concept

Chapter 5- Specification

This chapter covers the specification phase of the project. This includes a persona, interaction scenario, (non) functional requirements, functional architecture and time sequence diagram. Finally, the envisioned system is decomposed into functions and elaborated on to serve as a guide for the realization phase that will be discussed in chapter 6.

5.1 Persona

Emma is a 22 year-old female that performs track and field at a competitive level. She studies full-time at a university and lives close to both the university and the athletics track. During the times that she is not studying, she can often be found at the athletics track training for her next competition. She trains about 6-8 times a week and during the competition season, she competes close to once a week.

As many athletes do, Emma always wears a watch to guide her through her workouts. She likes receiving feedback on heart rate and the pace she is running, because it indicates to her how her workout is going. She feels satisfied with a training when she passes the goals set by herself and her trainer. Next to that, she likes to always have a phone within arm's reach to record her workouts so that she can watch them back and learn from the videos. The guidance of technological devices give her a sense of control and provide reassurance to her.

When the competition season gets closer, Emma gets excited to give her all during the competitions and achieve great times and distances. Because she trains very hard for it, competition pressure can built up to high levels. Although this pressure can have a positive effect on her performances, Emma tends to feel quite anxious in phases leading up to a competition. She thinks it would be helpful to have a tool that can provide her with feedback on her anxiety levels to create more self-awareness. Ideally, this tool may help her to get in control of her anxiety before competitions so she can use the pressure she experiences to her advantage.

5.2 Interaction Scenario

This section covers the interaction scenario for the HRV biofeedback system. It shows the use of the HRV biofeedback tool in its intended environment. This interaction scenario covers the whole preparation phase before the competition, from waking up to the user being physically fully prepared for the competition.

Interaction scenario- Competition day at the Hengelo track and field complex

1. It is 9:30h on competition day. Emma wakes up feeling well rested for her big day. Before starting her day, Emma puts on her sensing setup to allow for measuring of her heartrate data by the *HRV biofeedback system* and indicates via a slider which pre-competition phase she is in. At this moment, she is in pre-competition phase 1 (complete rest). The *HRV biofeedback system* measures Emma's heart rate in order to provide her with feedback on her competition anxiety before a competition.
2. Before she heads to the kitchen for breakfast, Emma indicates to the system that she has entered a different pre-competition phase, phase 2 (relaxed). After this, Emma brushes her teeth and takes a shower. At breakfast, she enjoys a bowl of oatmeal together with a hot cup of coffee to wake herself up. After breakfast, Emma packs her back, puts on her competition kit and heads to the car to leave for the competition.
3. Emma makes sure to fill up her *HRV biofeedback system* water bottle before heading out the door. As she enters the car and puts her *HRV biofeedback system* water bottle in the cup holder, she notices the bottle indicating a green light, meaning that her anxiety levels are

appropriate for the pre-competition phase she is currently in (phase 2, relaxed). She self-reflects and concludes that she is indeed feeling calm and ready to go to the competition.

4. Emma leaves her house at 10:30h, exactly as she planned. After a 30 minute drive, she arrives at the track. Emma waits 5 minutes before her training buddies arrive before they enter the competition track together.

5. As Emma and her friends head over to the competition area to collect their starting bibs, the *HRV biofeedback system* water bottle signals an orange light, indicating that Emma's anxiety levels are slightly higher than ideal for the current pre-competition phase (phase 2, relaxed). Emma concludes that she is indeed feeling the pressure rising as the competition gets closer, but acknowledges that the coffee she drank during breakfast might have an impact on her heart rate. She knows that the orange light is only meant to create awareness but does not require any actions yet.

6. About an hour and 15 minutes before the competition starts, at 11:45, Emma starts to prepare for her warm-up. She indicates this change in pre-competition phase by changing the slider to phase 3 (start of warm-up). After collecting her starting bib and noticing a rise in her anxiety levels, she sat down for a little bit and listened to some music to calm down. As she hoped, the system confirms by signalling a green light that her anxiety levels have reached the most appropriate level again. She feels ready to start her warm-up.

7. Emma starts her warm-up by running for about 10 minutes on the grass around the track. With her favourite music playing in her headphones, she follows up the running with some stretching exercises. Moving around, Emma notices she is getting a bit thirsty. Luckily, she has put her *HRV biofeedback system* water bottle right next to where she was doing her exercises so she can easily take a sip when needed. When grabbing the water bottle to drink some water, Emma notices that the lights have turned green. The warm-up has created a change in Emma's heart rate data, but because she is in a different pre-competition phase (phase 3, start of warm-up), the anxiety levels are appropriate for now.

8. As the competition is getting closer, Emma notices the bottle has turned orange and then turns red after some more time, meaning that the anxiety levels have reached a too high level and she may benefit from trying to calm down for a little bit.

9. As time is passing by and the warm-up progresses, Emma needs to put on her racing shoes and do some acceleration runs to conclude her warm-up. Emma indicates this change to a different pre-competition phase (phase 4, active warm-up) once again. The *HRV biofeedback system* water bottle indicates via a green light that in this pre-competition phase, her anxiety levels are appropriate.

10. After the warm-up, Emma heads over to the call-room to report her presence to the competition officials. The last pre-competition phase is reached and indicated by Emma by setting the slider to phase 5 (physically fully prepared for competition). She arrives in the call-room at 12:45 with 15 minutes left before the competition starts. This means she is in time and has to wait 15 minutes in the call-room before she is allowed to enter the competition area. While waiting in the call-room, Emma notices the bottle has turned blue, meaning that she is a little too calm for the pre-competition phase she is in. She knows that this blue light means that she would benefit from moving around to raise her anxiety level slightly to get herself in her most ideal state for her competition.

11. Emma gets up and moves around a bit, after which the system turns green, indicating appropriate anxiety levels to Emma. Emma enters the bathroom one last time in order to be fully ready for her competition. She fills up her *HRV biofeedback system* water bottle to be able to take a few sips of water during the remainder of the waiting time.

12. Emma is warned by the *HRV biofeedback system* water bottle via an orange light that her anxiety levels have risen slightly above appropriate for the pre-competition phase she is in. Emma knows that this level of anxiety is not the most ideal for her so she sits down and does some breathing exercises to try and calm herself down a little bit. After a few minutes, she feels calmer and the *HRV biofeedback system* water bottle signals a green light, indicating that Emma is now in the ideal anxiety range for her to perform well at the competition.
13. The officials notify the athletes that the competition is about to start and the athletes need to hand in all object that are not allowed in the competition area, such as smartwatches, phones and other electrical devices via which communication with others is possible. Because the *HRV biofeedback system* water bottle does allow for communication with another person visually via lights, Emma is not allowed to take it with her. She knew this beforehand, but feels ready for the competition because the *HRV biofeedback system* water bottle confirmed to her that her body is as ready for the competition as her mind is.
14. Emma removes the measuring system and hands it in, together with the *HRV biofeedback system* water bottle. The officials notify that it is time to leave for the competition so Emma follow their orders and leaves the call-room to go to the competition area.
15. Emma feels ready and excited for the competition. She is pleased that the *HRV biofeedback system* water bottle confirmed that she was physically ready to perform at her best.

5.3 System Requirements

This section discusses the system requirements, which are split up into functional and non-functional. Two categories of functional and non-functional requirements are formed: data collection and the feedback system.

5.3.1 Functional requirements

Data collection:

- Heart rate data must be measured and filtered
- Heart rate data must be stored
- Heart rate variability must be determined
- The user must be able to provide real-time input on perceived anxiety level and the pre-competition phase
- The perceived anxiety level and pre-competition phase must be discretized on a scale from 1 to 5

Feedback system:

- The system should provide visual feedback to the user
- The feedback provided must allow for personalization
- A compartment must hold all electrical components
- The compartment must be mounted under a regular water bottle

5.3.2 Non-functional Requirements

Measurement setup:

- Heart rate data is measured via the user's chest
- Digital filters for noise and artifact removal are applied if necessary
- Heart rate variability is calculated by the system using the peaks in the heart rate data
- Perceived anxiety levels and pre-competition phase are measured and categorized to a scale ranging from 1 to 5

Feedback setup:

- Visual feedback is provided using LEDs integrated into the feedback system
- The user can personalize the feedback via an actuator that is connected to the system
- The electrical components are stored away by creating a closed compartment, and hidden with a flexible LED matrix wrapped around it
- The compartment is cylinder shaped, with the width made fit to the bottom of a water bottle

5.4 Functional Architecture

This section covers the functional architecture of the system. It decomposes the system into levels, allowing for the system to be split up into smaller sections. The deepest level of the functional architecture shows the connection between inputs and outputs and graphically shows all the functions that take place in between the input and output.

5.4.1 Level 0

Figure 15 shows level 0 of the functional architecture of the system. Level 0 shows the system as one black box with the inputs and outputs connected to it. The relations between the in and outputs are not shown yet on this level, but will be specified in the deeper levels of the functional architecture.
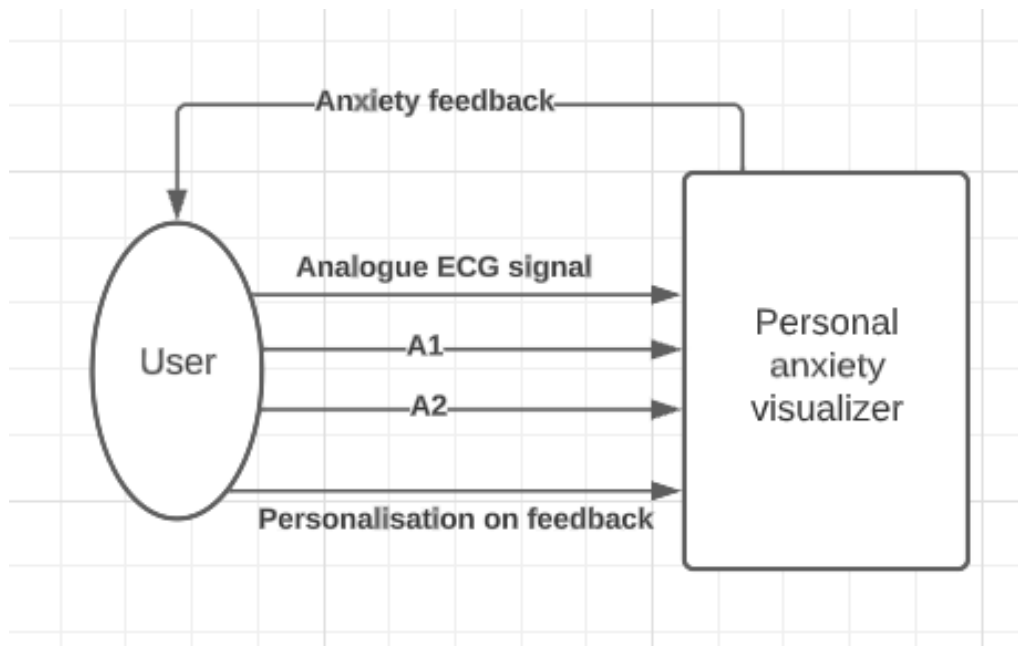
Figure 15: Functional architecture level 0

5.4.1 Level 1

Figure 16 shows level 1 of the functional architecture of the system. Level 0 consist of the user and three functions: the logger, the annotation classifier and the HRV feedback system. The user provides data as input for the first two functions. The logger takes an analogue ECG signal and as input and outputs the HRV class. The annotation classifier takes analogue values for A1 and A2 and classifies these into levels. A1 represents the perceived anxiety level of the user. A2 represents the pre-competition phase that the athlete is currently in. The outputs are digital numbers for the perceived anxiety level (A1 levels) and the pre-competition phase (A2 phase). The HRV feedback system takes the HRV class from the logger, together with the two inputs from the annotation classifier (A1 level and A2 phase) and translates this to anxiety feedback, which it outputs back to the user. The user has the option to personalize the feedback. This is given as input to the HRV feedback system. This allows for the user to provide feedback on the feedback, which in the future could serve as a starting point for a self-learning feedback system that learns from the input from the user.
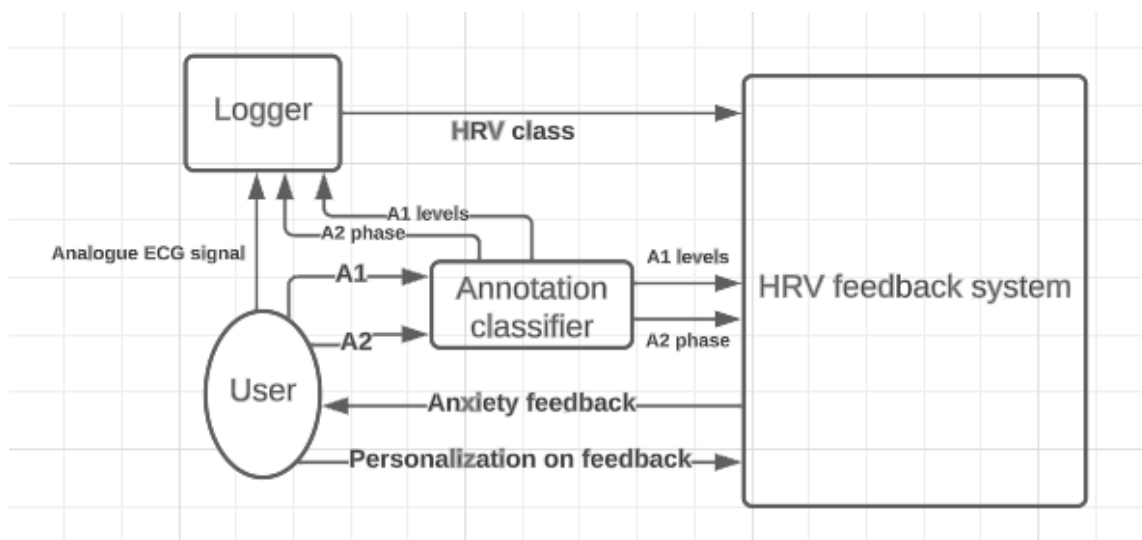
Figure 16: Functional architecture level 1

5.4.2 Level 2

Figure 17 shows level 2 of the system, which looks into the system functions slightly more in depth. The analogue ECG signal coming from the user goes into the signal pre-processing function, where a digital ECG data is created. This digital ECG data goes into the HRV processing function, which also takes time as input coming from the timing function. The HRV processor creates HRV values, which are send to the HRV classifier and saved in the storage function. This HRV classifier creates HRV classes, which are send to the HRV feedback system. These HRV classes are the input for the anxiety translator function, together with the perceived anxiety levels (A1 levels) and pre-competition phase (A2 phase), coming from the annotation classifier function. The anxiety translator translates the inputs to a feedback class, which is send to the anxiety visualizer function. This anxiety visualizer function takes the feedback class and creates the anxiety feedback that is output to the user. The user then personalizes the feedback by providing feedback on it.
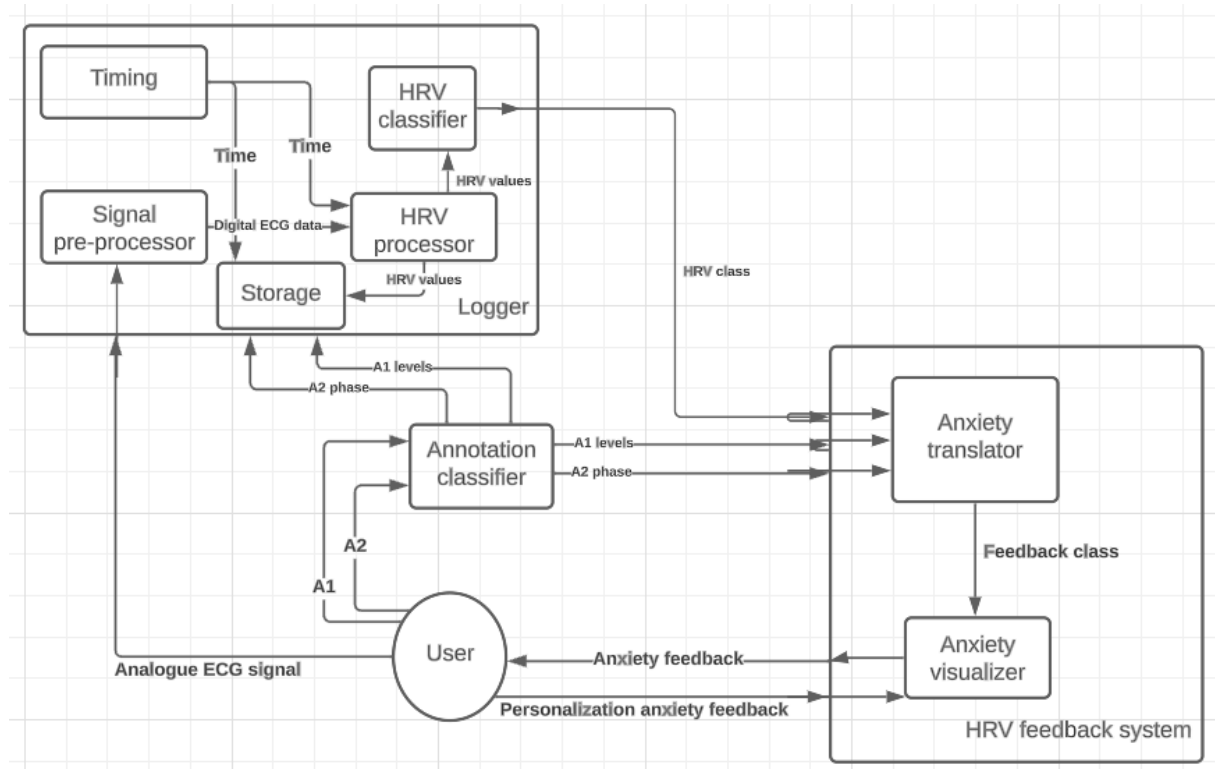
Figure 17: Functional architecture level 2

5.4.3 Level 3

Figure 18 shows level 3 of the functional architecture, which describes the system more in depth. All functions described in this section are further specified in section 5.4.4. The analogue ECG signal coming from the user is send to the ECG data acquiring function, which creates digital ECG data and sends this to the ECG data filtering function. This function filters the ECG data, after which it sends the digital ECG data to the HRV processor where HRV values are created from the digital ECG data and the time coming from the timing function. The HRV values are then send to the HRV classifier, which creates HRV classes to be send to the feedback classifier function within the HRV feedback system.

The storage function takes time, digital ECG data, perceived anxiety levels (A1 levels) and pre-competition phase (A2 phase) and stores this data.

The annotation classifier outputs A1 levels and A2 phases of which the last one is send to the lookup pre-competition phase function, which determines and outputs the pre-competition phase. The pre-competition phase is send to the feedback classifier, where the HRV levels and perceived anxiety levels (A1 levels) also come in. The feedback classifier takes these inputs and creates a feedback class as output, which is send to the anxiety visualizer. The anxiety visualizer takes the feedback type as input and creates anxiety feedback which is output to the user. The user then personalizes the feedback by providing feedback to the feedback system. The feedback classifier and anxiety visualizer functions are further specified in sections 5.6.8 and 5.6.9 respectively.
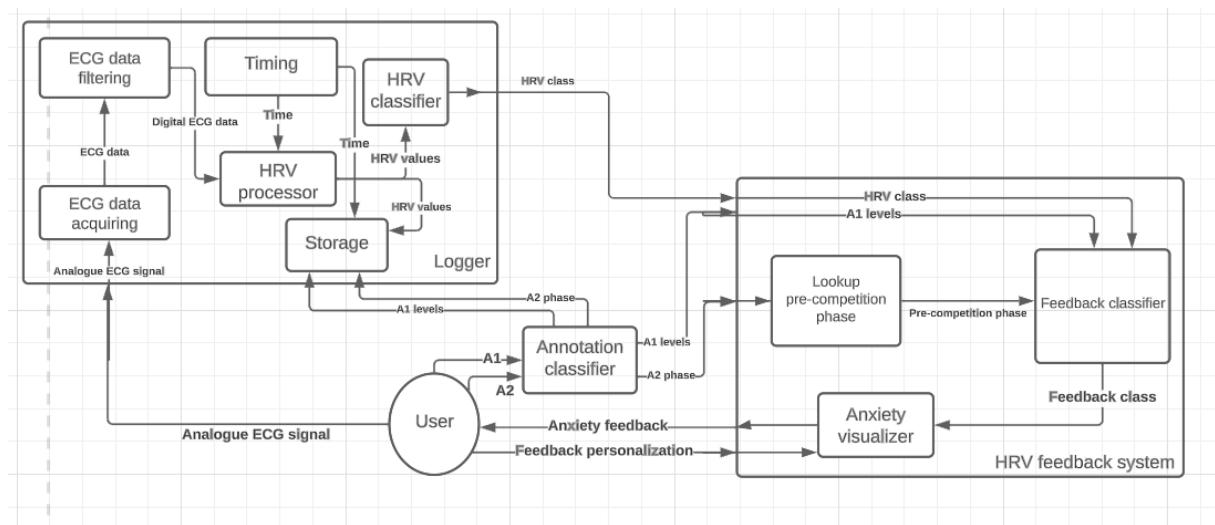
Figure 18: Functional architecture level 3

Chapter 5.5- System decomposition

This section covers a decomposition of the system, where the function blocks defined in the functional architecture (Figure 18) are further specified.

5.5.1- ECG data acquiring

The ECG data acquiring function block takes an analogue ECG signal from the user and transforms this to ECG data. The analogue ECG signal needs to be measured by this function block and digitalized.

5.5.2- ECG data filtering

The ECG filtering function block aims at outputting a filtered ECG signal suited for HRV processing. This means that noise and motion artefacts needs to be removed if present in the ECG data. According to literature [30], three steps need to be taken to filter the data. First, a high-pass filter of approximately 0.5 to 0.6 Hz to remove baseline wander. Then, a notch filter of 50 or 60 Hz to eliminate powerline interference. Lastly, a low-pass filter of 100 Hz to remove EMG noise.

5.5.3- HRV processor

The HRV processing function block takes the digital, filtered ECG data and creates HRV values from this. This is done through multiple steps including peak detection, a sliding window and HR measure calculations. The sliding window allows for peak detection within a timeframe of constant width, moving over the dataset. Peaks need to be detected to allow for HRV calculations, since HRV concerns R-R peaks.

5.5.4- HRV classifier

The HRV classifying function block takes the HRV values calculated by the HRV processor and classifies these into 5 levels, ranging from 1 to 5. The lowest HRV value falls into level 1 and the highest into level 5.

5.5.5- Storage

The storage function stores four data streams into a csv file: time, HRV values, perceived anxiety levels and pre-competition phase. This block will not be actively used, but allows for the saved data to be used later.

5.5.6- Annotation classifier

The annotation classifier function block classifies two streams of measured values from the user into five levels each. One represents the perceived anxiety levels, the other represents the pre-competition phase. Both these inputs are classified into five levels ranging from 1 to 5. The perceived anxiety levels are measured analogue and categorized. The table below shows the pre-competition phases with a short description.

Pre-competition phase #	Pre-competition phase description
1	Complete rest, athlete not moving
2	Relaxed
3	Start of warm-up phase (jogging, stretching, relaxed exercises)
4	Active warm-up (acceleration runs and other active exercises)
5	Athlete in call-room, physically fully prepared for the competition

Table 1: Table describing the pre-competition phases

5.5.7- Lookup pre-competition phase

The lookup pre-competition phase function block contains all the pre-competition phases (1-5) and looks up which of these five the current input is. This information is send to the feedback classifier.

5.5.8- Feedback classifier

The feedback classifier function block gets HRV levels, perceived anxiety levels and a pre-competition phase as inputs. The goal of this function is to compare the levels of HRV and perceived anxiety levels and check whether their relation is appropriate for the user in the current pre-competition context. The user provides a table for this function that serves as the decision tree determining the feedback class. The user needs to determine for themselves what they feel appropriate relations are for the HRV levels and perceived anxiety levels in the context of the pre-competition phase. For example, if the user is in pre-competition phase 1 (complete rest) and their perceived anxiety levels and HRV levels are both a 5 (very high), the user needs to determine if this is appropriate or not. If the user thinks this relation is appropriate, they will put one of the four numbers in the table with its appropriate meaning. The feedback classifier determines from these decisions what feedback needs to be given to the user. The feedback is given as one of four numbers: 0 (orange), 1 (blue), 2 (green) or 3 (red). Table 2 shows an empty version of this feedback classifier table.

Pre-competition phase = 1, 2, 3, 4 or 5	HRV level = 1	HRV level = 2	HRV level = 3	HRV level = 4	HRV level = 5
Perceived anxiety level = 1	Feedback class	Feedback class	Feedback class	Feedback class	Feedback class
Perceived anxiety level = 2	Feedback class	Feedback class	Feedback class	Feedback class	Feedback class
Perceived anxiety level = 3	Feedback class	Feedback class	Feedback class	Feedback class	Feedback class
Perceived anxiety level = 4	Feedback class	Feedback class	Feedback class	Feedback class	Feedback class
Perceived anxiety level = 5	Feedback class	Feedback class	Feedback class	Feedback class	Feedback class

Table 2: Example of feedback classifier table

5.5.9- Anxiety visualizer

The anxiety visualizer function block takes the determined feedback and creates the actual feedback from this. This block determines the feedback that is shown to the user when the feedback type is a 0, 1, 2 or 3. The feedback that is shown to the user is visual feedback, using LEDs. Four colours are chosen to display the feedback: blue, green, orange and red. The table below shows the relations between the feedback type, feedback number and the colour of the LED.

Feedback class	Colour hue of the LED	Feedback type
0	Orange	Anxiety levels are slightly high for the current pre-competition phase, user needs to be aware, but no action is needed.
1	Blue	HRV levels are too low for the current pre-competition phase. User might benefit from getting slightly more active.
2	Green	Anxiety and HRV levels are appropriate for the current pre-competition phase, no action needed.
3	Red	Anxiety levels are too high for the current pre-competition phase. User might benefit from calming down.

Table 3: Table describing the workings of the anxiety visualizer function block

5.5 Flow chart

This section covers the flow chart of the system, which is shown in Figure 19. The flow chart shows the systems functions in their appropriate time order. It starts with the user turning on the system, goes through all the functions of the system and ends again with the user when the feedback is shown.
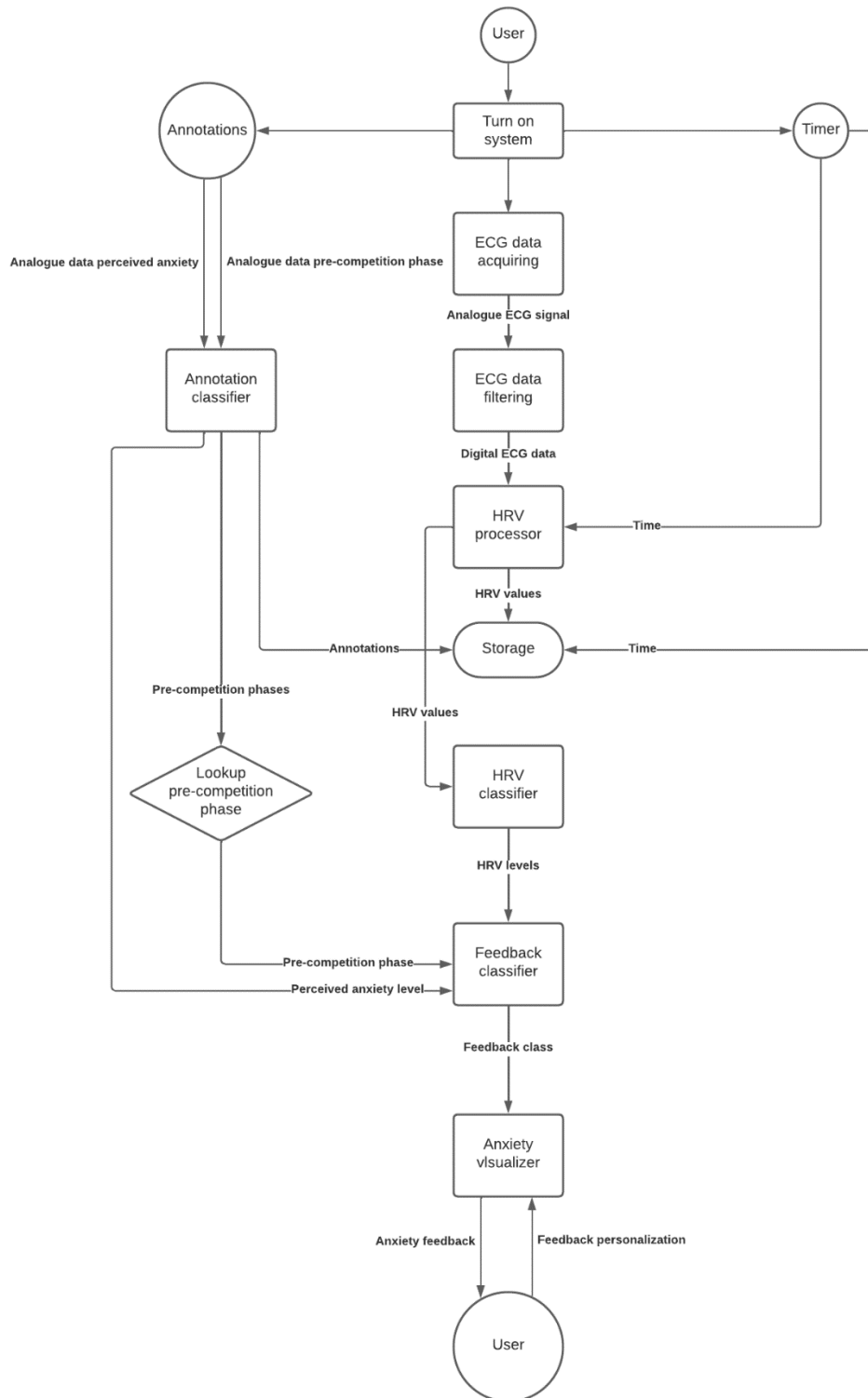
Figure 19: Flow chart of the HRV biofeedback system

Chapter 6- Realization

This chapter discusses the realization part of the project. This includes the description of the realized system, decomposed in several parts, the integration of these parts and finally a functional system test.

6.1- System description

This section describes the realization phase from the raw data measured to the feedback that is shown to the user. As mentioned in chapter 5, the specification phase, the functional architecture serves as a guide for the realization phase. First, the analogue ECG signal is filtered and digitalized, after which it is send through multiple steps to end up with HRV levels, which are then compared to the other two inputs (perceived anxiety levels and pre-competition phase), to then determine what feedback is shown to the user.

During the realization phase, problems have been ran into which have caused some major changes to the system. The first one is that the system will consist of several operational phases and will not yet run real-time. In the first phase, data is acquired on the ECG and the annotations. This data is saved to a csv file, which can then be imported into Python for phase two. In phase two, Python filters the data, categorizes it and calculates what feedback needs to be displayed to the user and displays this accordingly. The feedback that the user can give to the system is done during the displaying of the feedback and influences the feedback that is shown accordingly.

The hardware and software components used in the realization part of the project can be found in Appendix 1 and 2.

6.1.1- Data acquiring (ECG measuring and annotations)

Schematic of measurement setup

In order to measure ECG data and data on the perceived anxiety levels and pre-competition phase, a measurement setup is built. This setup consists of an Arduino Uno with an Olimex shield on top. Connected to this Olimex shield via wires are ECG electrodes which are attached to the person measured via the Einthoven method (see chapter 3.1.3). This part of the setup can be seen in Figure 21 and covers the measuring of ECG data, which is read by the Arduino Uno via the Arduino IDE. The electrode placement for this measurement setup is shown in Figure 20.
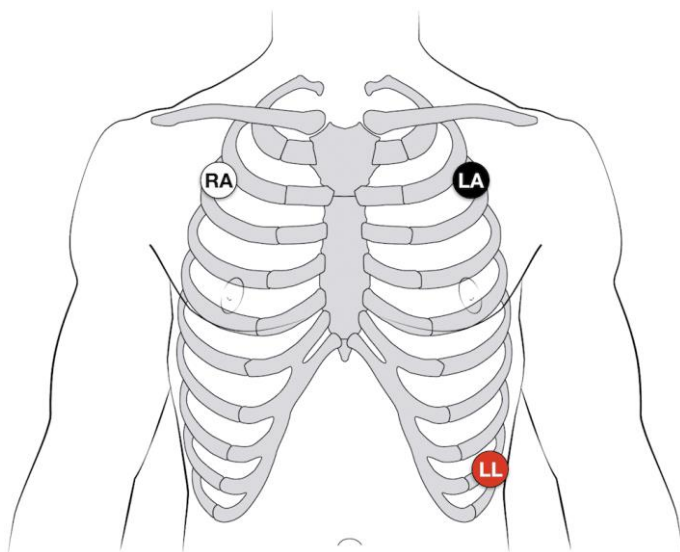
Figure 20: ECG electrode placement

Also read by the Arduino Uno via the Arduino software are the analogue values of two sliding potentiometers, representing the scales for the perceived anxiety levels and pre-competition phase. These potentiometers are connected to the Arduino Uno via wires. This setup can be seen in Figure 22Figure 22. The discretisation of the values is covered in section 6.1.5.
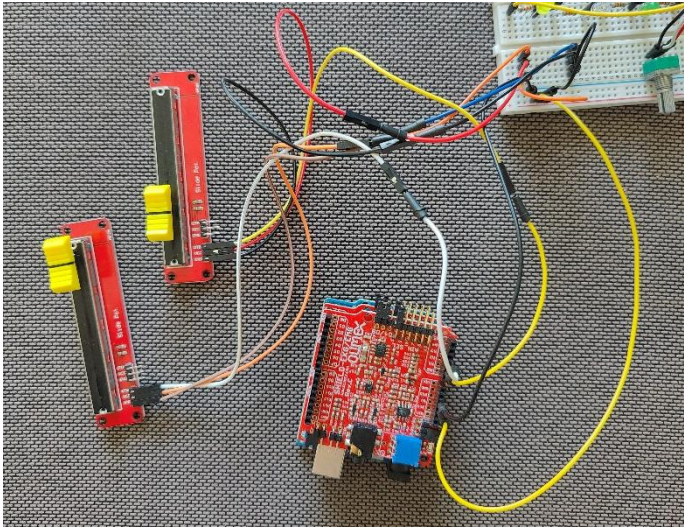
Figure 21: ECG measuring setup with Arduino Uno, Olimex shield and two sliding potentiometers
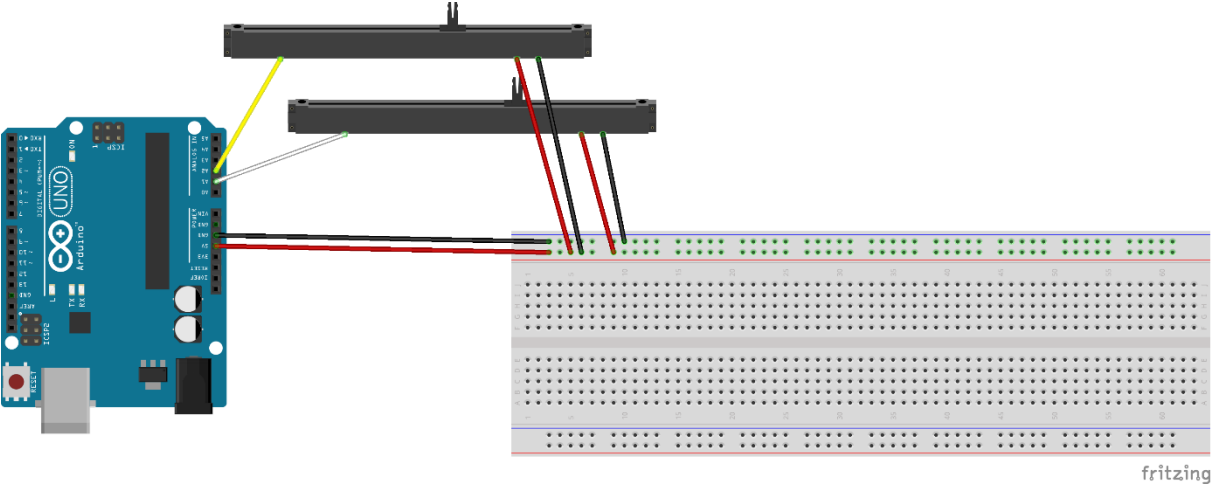
Figure 22: Sliding potentiometers setup

The values measured by this setup are saved from the Arduino software to a Excel file via the software PuTTY, using serial communication. This means that the Arduino writes the values onto a serial port, which the software PuTTY then reads from that serial port.

Arduino code for reading ECG signal and potentiometer values

In the Arduino software, code is written in order to read the ECG signal and potentiometers. This code can be seen in Figure 23.

```
1
2    void setup() {
3      Serial.begin(9600);
4      Serial.setTimeout(1);
5
6    }
7
8    void loop() {
9      //Serial communication
10     Serial.print(analogRead(A0)); //ECG data
11     Serial.print(";");
12     Serial.print(millis());
13     Serial.print(";");
14     Serial.print(analogRead(A1)); //PA potmeter
15     Serial.print(";");
16     Serial.println(analogRead(A2)); //PC potmeter
17
18     // about 256Hz sampling rate
19     delayMicroseconds(3900);
20   }
```

Figure 23: Arduino code for reading ECG data and two potentiometers

6.1.2- ECG data filtering
Literature on filtering and MATLAB filter implementation

Measuring raw ECG data is usually rather noisy, which can mostly be solved by filtering. According to literature [30], ECG filtering usually takes three standard steps to remove unwanted noise and artifacts form the raw signal. These steps are tested on 60 seconds of raw ECG data via MATLAB (version R2020a). A time of 60 seconds is chosen because it allows for stable data with enough peaks present to test filter settings and perform peak detection. The first ten seconds of measuring seem to have a baseline drift, which stabilizes after approximately 10 seconds. Therefore, 60 seconds proves to be appropriate for designing and testing the filter.

The first step is to apply a high-pass filter with a cut-off frequency of approximately 0.5 to 0.6 Hz to remove baseline wander. After testing different values in MATLAB, a high-pass filter with a cut-off frequency of 4 Hz seemed to be the most appropriate for the measurement setup. Since literature mentioned that increased movement of the body can cause an increase in the frequency content of the baseline wander. Therefore, 4 Hz is chosen based on both literature and testing. In Figure 24, the effect of the high-pass filter on 60 seconds of a raw ECG signal can be seen. During these 60 seconds, the person being measured switched between sitting and standing every ten seconds.
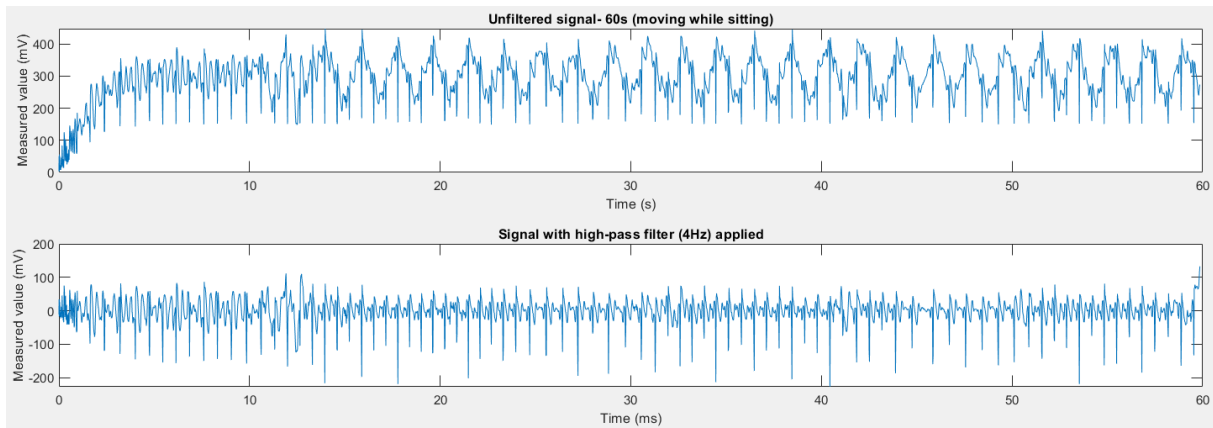
Figure 24: Raw ECG signal (top) and ECG signal with high-pass filter (4 Hz) applied (bottom)

The data is flipped in order to have the peaks point upwards in the positive direction, which allows for easier use of a peak-detection function with minimum height threshold later. When applying a peak detection function on this signal with a minimum height of 92, a lot of peaks are already correctly identified. However, some smaller peaks are not identified yet, which is why the signal needs some more filtering. Another thing worth mentioning is that at a time of approximately 12-13 seconds, the signal seems to contain more noise, possibly caused by electrical interference or movements from the measurement person. This noise causes multiple values to cross the minimum peak height of 92, but these are not peaks that we want to detect because they are not true heart rate peaks. The flipped data with a peak-detection function applied can be seen in Figure 25.
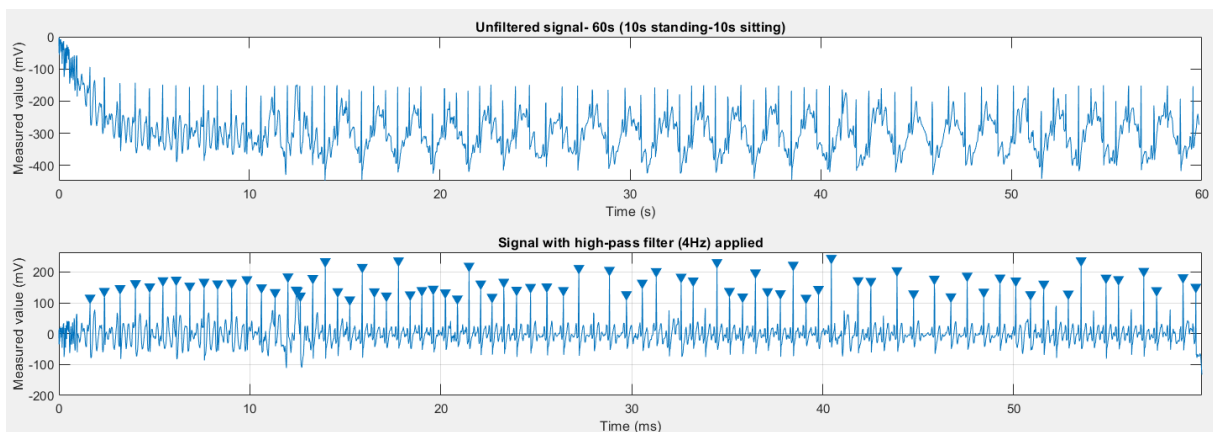
Figure 25: Raw ECG signal (top) and ECG signal with high-pass filter (4 Hz) and peak detection (bottom)

The second step literature suggests for filtering an ECG signal is applying a notch filter of 50 or 60 Hz to eliminate powerline interference. This is noise coming from electromagnetic fields caused by powerlines [30]. Figure 26 and Figure 27 show the raw ECG signal, and the ECG signal with a high-pass filter of 4 Hz and a notch filter of 50 Hz (Figure 26) or 60 Hz (Figure 27) applied. Not much difference is spotted between the two figures, which may be caused by a lack of powerline interference. Although literature suggests adding this step in the filter, in this case the choice is made to not use one as there seems to not be any benefits from adding it. Because the project currently only uses this specific measurement setup, it is a fair choice to not use the notch filter. When using a different measurement setup or when measuring in a different environment, the notch filter might need to be added.
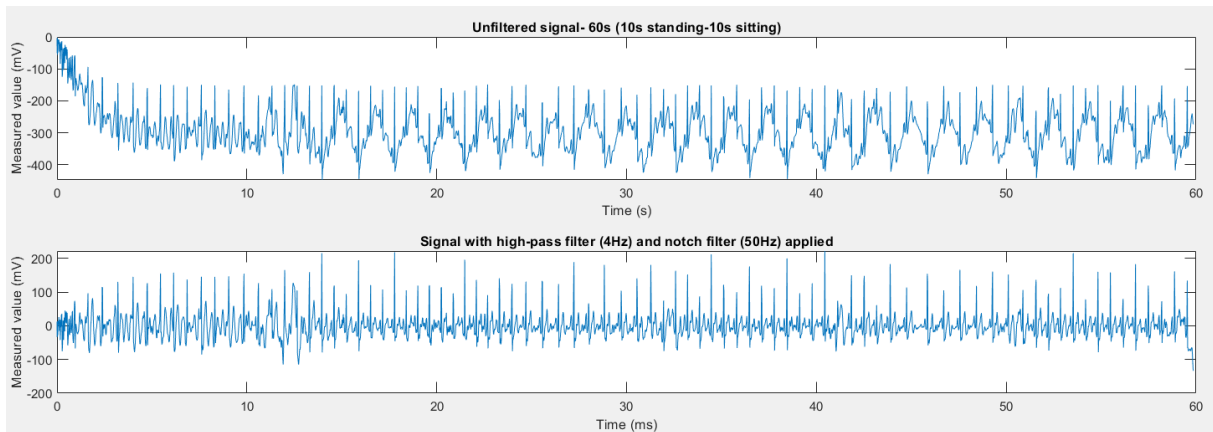
Figure 26: Raw ECG signal (top) and ECG signal with high-pass filter (4Hz) and notch filter (50 Hz) applied (bottom)
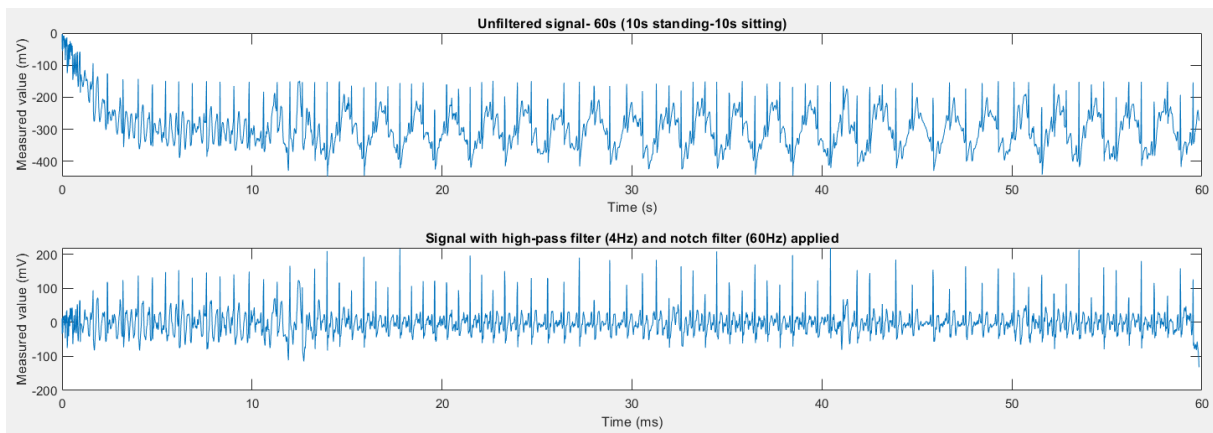
Figure 27: Raw ECG signal (top) and ECG signal with high-pass filter (4Hz) and notch filter (60 Hz) applied (bottom)

Lastly, literature suggest the use of a low-pass filter with a cut-off frequency of 100Hz to remove EMG noise. Variations are tested here, but the 100Hz cut-off frequency provided the best result, which can be seen in Figure 28.
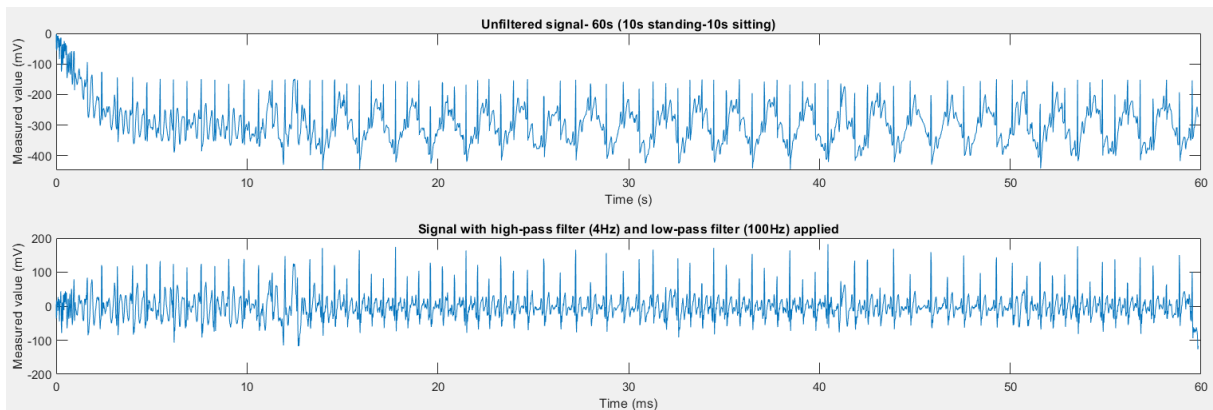
Figure 28: Raw ECG signal (top) and ECG signal with high-pass filter (4Hz) and low-pass filter (100Hz) applied (bottom)

A peak detection function [31] is applied to demonstrate the peaks detected in the filtered signal, which can be seen in Figure 29. A minimum height of 90 is set, which allows for a large part of all peaks to be detected, but some peaks still have a too low amplitude to pick up.
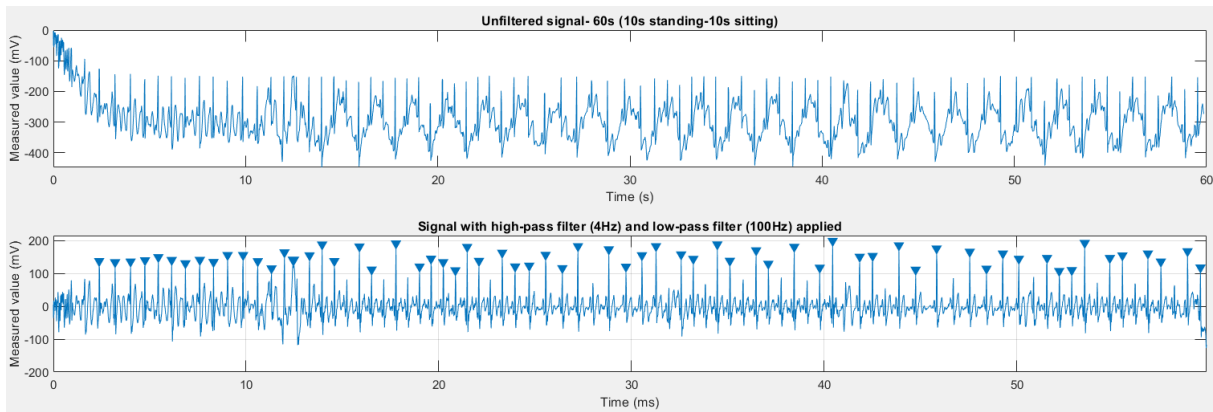
Figure 29: Raw ECG signal (top) and filtered ECG signal with peak detection (bottom)

In conclusion, the following filtering steps are applied to obtain a signal from which the peaks can be detected most optimally:

- High-pass filter with cut-off frequency of 4 Hz to remove baseline wander
- Low-pass filter with cut-off frequency of 100Hz to remove EMG noise

The signal is flipped over the x-axis in order to have the peaks pointing in the positive direction. This allows for setting a minimum peak height in the Python code that detects the peaks. After filtering the data in MATLAB, a minimum height of 90 seems to be the most appropriate value to detect as many peaks as possible, without detecting parts of the signal which are not peaks.

MATLAB code for filtering ECG signal

In Figure 30, the MATLAB code can be seen which is used for filtering the raw ECG data and plotting it.

```matlab
data = secondsstandingup10ssittingdown10s.(1)*-1; %Reverse data to have peaks pointing upwards
time = secondsstandingup10ssittingdown10s.(2)/1000; %Convert ms to s

Fs = 256;    % Sampling frequency

tiledlayout(2,1)

data_HPF = highpass(data, 4, 256);       %Cut-off frequency of 4Hz
data_LPF = lowpass(data_HPF, 100, 256); %Cut-off frequency of 100Hz

ax1 = nexttile;
plot(time, data);
title("Unfiltered signal- 60s (10s standing-10s sitting)")
xlabel("Time (s)");
ylabel("Measured value (mV)");

ax2 = nexttile;
plot(time, data_LPF);
findpeaks(data_LPF, time, 'MinPeakDistance', 0, 'MinPeakHeight', 90)
title("Signal with high-pass filter (4Hz) and low-pass filter (100Hz) applied")
xlabel("Time (ms)");
ylabel("Measured value (mV)");
```

Figure 30: MATLAB code for filtering and plotting ECG signal

Python filter implementation

The filter designed in MATLAB is implemented in Python using several libraries [32], [33]. Figure 31 shows the filtering result plotted via Python. A red line is added at a height of 90 to show the peaks in the filtered signal that exceed the threshold of 90.
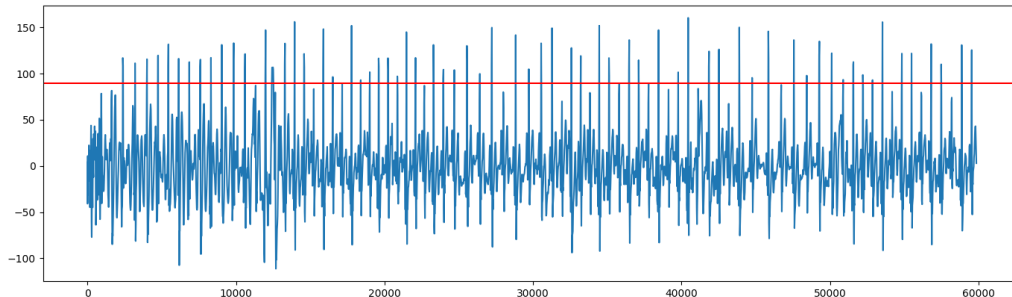
Figure 31: Result of the filter in Python

6.1.3- HRV processor

Determining HRV values from ECG data

To determine HRV values from ECG data, two steps need to be taken. First of all, we need to look into which HRV measure will be used as input for the feedback system. After this, we need to determine over what time interval the measurement needs to be done and the measure can be calculated in order to get an accurate outcome for this calculation.

Literature states that the conventional minimum recording for determining HRV measures is 5 minutes. However, ultra-short-term periods of 10, 30 and 60 seconds have been proposed. [27] RMSSD is a HRV measure that stands for the root mean square of successive RR interval differences. It is calculated by first calculating each successive time difference between heartbeats in milliseconds, after which each value is squared and the result is averaged before the square root of the total is obtained. [27] Literature on ultra-short-term periods has found that for the RMSSD, a period of 30 seconds works well compared to the conventional period of 5 minutes. [34]

In Python, the RMSSD can easily be determined by using a library called *hrvanalysis* [35]. This library calculates all time domain features of a signal and outputs these into a dictionary. From this dictionary, the RMSSD can be extracted.

To determine RMSSD over 30 seconds and allowing for this calculation to be done at a regular time interval, a sliding window technique is used. This means that a sampling window of 30 seconds is created, in which the calculation is performed. After this is calculation is done, the window moves a certain amount of time to again perform a calculation over 30 seconds. This new 30 second window overlaps partly with the old 30 second window. This is because for this project, a update time of 5 seconds is chosen. The reasoning for this is explained in section 6.1.4.

6.1.4- HRV classifier
Determining HRV levels

The HRV levels are determined by categorizing the HRV values into five categories ranging from 1 to 5. The HRV values are calculated over 30 seconds via a sliding window, which allows for one section of 30 seconds long to be compared to the next section of 30 seconds, happening one time interval later. This means that for a system running real-time, it takes 30 seconds for the system to determine the initial HRV level, after which this can be updated at a desired time interval. Because this project does not run real-time, it only takes a few seconds to determine a value for the first 30 seconds.

Updating the HRV level every second or even every time interval seems too much, therefore a more appropriate time interval of 5 seconds is chosen. This means that the HRV is determined over a period of 30 seconds, and updates every 5 seconds, meaning that every 5 seconds, the feedback can change if a change in the HRV levels is detected.

The system as it is now cannot determine the full range of HRV levels, since the current measurement setup is wired and does not allow for data measuring whilst moving around. This means that only HRV levels in rest whilst sitting or standing still can be determined right now. In the future, this measurement setup needs to be exchanged for a wireless one (e.g. Zephyr devices), allowing for the full range of HRV levels to be determined. In this version of the project, the HRV levels can be input manually in order to demonstrate all HRV levels.

6.1.5- Annotation classifier
Classifying perceived anxiety level and pre-competition phase

The perceived anxiety level and pre-competition phases are indicated by the user via a linear potentiometer in the shape of a slider. These sliders are connected to the Arduino, which reads the analogue values. The analogue values range from 0 up to and including 1023. The anxiety level and pre-competition phase are set by the user by sliding one of the sliders. The slider values are categorized in order to link a number of 1 to 5 to the analogue value ranges. This allows the user to input the two annotations in one of 5 levels. Number one corresponds with the first 20% of the values of slider, number two with the second 20% of the values on the slider, and so forth. This means the following categorization:

- Level 1- analogue values 0-205
- Level 2- analogue values 205-410
- Level 3- analogue values 410-615
- Level 4- analogue values 615-820
- Level 5- analogue values 820-1023

Pre-competition phases

As mentioned in the previous section, the pre-competition phase can be indicated by the user, which can be seen as a mode in which the feedback is determined. These phases are introduced because the relation between HRV data and perceived anxiety levels differ in appropriation within different phases of the pre-competition phase. For example, there is a big difference between experiencing low anxiety and the physiological data confirming low anxiety levels when in phase 1 or in phase 5. When in phase 1, a low anxiety level and calm physiological data is desired, but when in phase 5, a higher heart rate is more appropriate in the context. The pre-competition phases are defined in chapter 5.6.6.

6.1.6- Feedback class decider

To determine what feedback is displayed to the user, a decision tree is created in which relations between HRV levels (HRV_level) and perceived anxiety levels (PA_level) are compared in the context of the current pre-competition phase (PC_phase). This decision tree is filled in with colours that represent the four different feedback classes defined in chapters 5.6.8 and 5.6.9: blue, green, orange and red (see Table 3).

This table is incorporated in Python to determine what feedback is displayed to the user. The table is based on individual desires of the user, in this particular case the student developing this system. To demonstrate the possibilities for adjusting the feedback tool for any other user within the target group, another table is created based on the personal experience and individual desires of another user within the target group. This table can be seen in Chapter 7 (Evaluation), Table 7.

PC_phase 1	HRV_level = 1	HRV_level = 2	HRV_level = 3	HRV_level = 4	HRV_level = 5
PA_level = 1	green	green	orange	orange	red
PA_level = 2	green	green	orange	orange	red
PA_level = 3	orange	orange	orange	red	red
PA_level = 4	orange	orange	red	red	red
PA_level = 5	red	red	red	red	red

PC_phase 2	HRV_level = 1	HRV_level = 2	HRV_level = 3	HRV_level = 4	HRV_level = 5
PA_level = 1	green	green	green	orange	red
PA_level = 2	green	green	green	orange	red
PA_level = 3	green	green	green	orange	red
PA_level = 4	orange	orange	orange	orange	red
PA_level = 5	red	red	red	red	red

PC_phase 3	HRV_level = 1	HRV_level = 2	HRV_level = 3	HRV_level = 4	HRV_level = 5
PA_level = 1	blue	green	green	green	orange
PA_level = 2	blue	green	green	green	orange
PA_level = 3	orange	green	green	green	orange
PA_level = 4	orange	green	green	green	orange
PA_level = 5	orange	orange	orange	orange	orange

PC_phase 4	HRV_level = 1	HRV_level = 2	HRV_level = 3	HRV_level = 4	HRV_level = 5
PA_level = 1	blue	blue	green	green	orange
PA_level = 2	blue	blue	green	green	orange
PA_level = 3	blue	blue	green	green	orange
PA_level = 4	blue	orange	green	green	orange
PA_level = 5	blue	orange	orange	orange	orange

PC_phase 5	HRV_level = 1	HRV_level = 2	HRV_level = 3	HRV_level = 4	HRV_level = 5
PA_level = 1	blue	blue	blue	green	green
PA_level = 2	blue	blue	blue	green	green
PA_level = 3	blue	blue	green	green	green
PA_level = 4	blue	blue	green	green	green
PA_level = 5	blue	blue	green	green	green

Table 4: Decision tree that determines feedback actions

6.1.7- Anxiety visualizer

The Python code outputs the type of feedback that needs to be shown to the user. This feedback is a colour that needs to be physicalized to show it to the user. It is chosen to display this feedback to the user via four coloured LEDs, representing the four feedback options: green, yellow, red and blue (see Table 3). Every five seconds, the code outputs a feedback type, meaning that every five seconds, it is determined which LED turns on. Only one LED can be on at a time.

6.1.8- User feedback on the given feedback

In future versions of this project, the decision tree mentioned in section 6.6 will serve only as a base for the feedback determining algorithm. The user will provide input while using the system, which allows for a self-learning algorithm to be developed. This means that the feedback determining will update based on the users feedback on it. To demonstrate the potential implementation of this feedback, simple feedback is incorporated in this early version of the project. This simple feedback is implemented by using a potentiometer, serving as a dimmer. When the potentiometer is turned to a certain value, the feedback shown to the user changes. With the potentiometer in the middle, the feedback is shown as it is calculated earlier. When the user turns the potentiometer to the lowest value, the feedback turns off completely, indicating that the user does not want this feedback at this time. When the potentiometer is turned to the highest value, the feedback LEDs start blinking instead of being on constantly, indicating that the feedback shown was too low and the user would prefer higher feedback. When the potentiometer is between these extreme values and in the middle, the user indicates that the feedback shown is okay and does not need to change.

In future iterations of this project, this simple feedback on the feedback system can serve as a base for the self-learning algorithm that will learn from this feedback and update the decision tree accordingly.

6.2- Integration

The system consists of two subsystems, which are used independently. The first subsystem is the measurement or data acquiring system. Here, ECG data is measured, as well as the two user inputs: perceived anxiety level and pre-competition phase. The second subsystem is the feedback system, which displays the feedback to the user via four LEDs. This system also allows for the user to provide feedback on the feedback via a potentiometer. These two separate systems work at different time moments and are not fully integrated. However, they are rather linked together by one Python file containing code that imports the acquired data from the first system, does multiple calculations on this data and calculates the feedback that is displayed to the user via the second setup.

Both setup systems are divided into multiple blocks, which are developed separately and then added together. For example, first the ECG measurement block and filter were built, after which one step at a time, the calculation blocks were added.

6.3- Functional System Test

In this section, the functional requirements from chapter 5 (section 5.3.1) are tested to check to what extend they are fulfilled. As in chapter 5, the functional requirements are split up into two categories: data collection and the compartment under the water bottle. Problems with the measurement setup early in the specification and realization phase caused a lot of delay in these phases and meant that more work than planned had to be done in order to fulfil the requirements regarding the data collection. This results in the first part of the requirements to be much more fulfilled than the second part. Some simple feedback is provided in the end, but not worked into a prototype for the water bottle described in chapter 4 (section 4.4). To create something more than just visual feedback, another user input was added in the later stages of the project as a first version of user feedback on the feedback. The final system that is developed during this project is not the fully functional prototype that was desired, but serves rather as a stepping stone for further development.

6.3.1- Procedure

The functional requirements are added to a table, after which the system is checked for each of the functional requirements in order to check via a scale to what extend they are fulfilled. The scale ranges from 1 (not fulfilled) to a 5 (completely fulfilled).

6.3.2- Results

Data collection

Functional requirement	Fulfilled 1-5 (1 not fulfilled, 5 completely fulfilled)	Comments
Heart rate data must be measured and filtered	5	HR data is measured and filtered
Heart rate data must be stored	5	HR data is stored in a csv file
Heart rate variability must be determined	4	HRV measures are calculated, but can only be determined in rest, limiting the range that can be determined
The user must be able to provide real-time input on perceived anxiety level and pre-competition phase	3	The inputs are provided whilst measuring the data. The feedback is not given real-time, meaning input on perceived anxiety level and pre-competition phase cannot be given whilst the feedback is given
The perceived anxiety level and pre-competition phase must be discretized on a scale from 1 to 5	5	The perceived anxiety level and pre-competition phase are indicated via a linear potentiometer of which the values are categorized into five levels

Table 5: Functional requirements regarding the data collection

The feedback system

Functional requirement	Fulfilled 1-5 (1 not fulfilled, 5 completely fulfilled)	Comments
The system should provide visual feedback to the user	4	The system provides visual feedback via four simple LEDs
The feedback must allow for personalization	4	The user can personalize the given feedback using a potentiometer
A compartment must hold all electrical components	1	No compartment is created due to time limitations
The compartment must be mounted under a regular water bottle	1	No compartment is created due to time limitations

Table 6: Functional requirements regarding the compartment under the water bottle

From these tables, we can indeed conclude that the functional requirements of the first table are fulfilled quite decently. Although the system does not work in real-time at this moment, it has a lot of potential to work in real-time in the future. The data can already be measured and filtered in real-time. The determining of heart rate variability measures is not yet done in real-time and therefore the feedback is also not displayed real-time to the user. This is something that needs further development in order to make it work. Nevertheless, all the inputs that were wished for are present in the system.

As mentioned earlier, we can see that the functional requirements in the second table are less developed, especially those regarding the development of a compartment to hold the electronics. Due to the earlier mentioned issues, this could unfortunately not be developed yet. The first two functional requirements regarding the providing of visual feedback and personalization of this feedback are partly fulfilled. The feedback is shown to the user visually via four simple LEDs. The user has the option to personalize the feedback via a potentiometer. If the potentiometer is set in the middle of its range, nothing happens. When the user turns the potentiometer to the lowest value, the feedback turns off, indicating that the user does not want to see feedback at that time. When the potentiometer is turned to the highest value, the feedback LED starts blinking. This indicates that the user would like to see a feedback of a higher class, meaning that if the feedback shown is orange, the user would feel that red is more appropriate to show at that time. This simple personalization system is supposed to be a tool to later develop a self-learning algorithm for determining the feedback class. The user. The user would in that case fill in the table as shown in Table 4, but the table would update accordingly to the feedback of the user.

Chapter 7- Evaluation

This chapter discusses a small user evaluation that was performed on the system. Because it is not fully functional yet, there was no possibility to perform a complete user evaluation. It has therefore been chosen to have the user evaluation focus on the personalization of the system and gather a few small opinions on the workings of the system. Table 7 shows a variation of Table 4, which represents the feedback decision table that determines the feedback class. Differences can be seen between the two tables, which illustrate the subjectivity in which competitive anxiety is experienced between different female athletes. The user mentioned that differentiating between pre-competition phases 1 and 2 was slightly difficult, but furthermore the workings of the system were clear.

PC_phase 1	HRV_level = 1	HRV_level = 2	HRV_level = 3	HRV_level = 4	HRV_level = 5
PA_level = 1	green	green	red	red	red
PA_level = 2	green	green	red	red	red
PA_level = 3	orange	orange	red	red	red
PA_level = 4	orange	orange	red	red	red
PA_level = 5	red	red	red	red	red

PC_phase 2	HRV_level = 1	HRV_level = 2	HRV_level = 3	HRV_level = 4	HRV_level = 5
PA_level = 1	green	green	orange	red	red
PA_level = 2	green	green	orange	red	red
PA_level = 3	green	green	orange	red	red
PA_level = 4	orange	orange	orange	red	red
PA_level = 5	red	red	red	red	red

PC_phase 3	HRV_level = 1	HRV_level = 2	HRV_level = 3	HRV_level = 4	HRV_level = 5
PA_level = 1	blue	blue	green	orange	red
PA_level = 2	blue	green	green	orange	red
PA_level = 3	green	green	green	orange	red
PA_level = 4	orange	orange	orange	orange	red
PA_level = 5	orange	orange	red	red	red

PC_phase 4	HRV_level = 1	HRV_level = 2	HRV_level = 3	HRV_level = 4	HRV_level = 5
PA_level = 1	blue	blue	blue	green	green
PA_level = 2	blue	blue	blue	green	green
PA_level = 3	blue	blue	green	green	orange
PA_level = 4	green	green	green	green	red
PA_level = 5	green	green	green	orange	red

PC_phase 5	HRV_level = 1	HRV_level = 2	HRV_level = 3	HRV_level = 4	HRV_level = 5
PA_level = 1	blue	blue	blue	green	green
PA_level = 2	blue	blue	blue	green	green
PA_level = 3	blue	blue	blue	green	green
PA_level = 4	green	green	green	green	green
PA_level = 5	green	green	green	green	orange

Table 7: Table with feedback class decisions filled in by a potential user

Chapter 8- Discussion & Conclusion

This section covers the discussion and conclusion section of the project. It answers the research question and its accompanying sub questions. As mentioned in Chapter 1, the main research question is stated as follows:

> *How to develop an HRV biofeedback tool to signal anxiety levels to female competitive track & field athletes?*

Accompanying sub questions:

> *What type of feedback modality is suited for the environment in which the HRV biofeedback tool is meant to be used?*

> *To what extend is it possible the athlete with real-time feedback during a competition/training?*

In order to develop an HRV biofeedback tool to signal anxiety levels to female competitive track and field athletes, multiple aspects need to be thought of. These include amongst others the measuring of heart rate data, calculations to get heart rate variability measures and calculations to link heart rate variability measures to anxiety levels. Next to this, a time interval must be determined within which HRV measures can accurately be determined. Additionally, feedback must be created from all the calculations, which must then be signaled to the user.

Measuring heart rate data must be done in a way that allows for the complete spectrum of heart rate to be measured, from minimum to maximum heart rate. The current measurement setup does not allow for this to be the case. The measurement setup must also allow for the time intervals between consecutive heart rate peaks to be calculated, which is possible with the current measurement setup.

Calculations to get heart rate variability measurements from heart rate data are found in literature. Heart rate variability has a lot of useful measures, of which the standard measurement time interval to get an accurate outcome is 5 minutes. In order to provide the user with real-time feedback, a shorter time interval is desired. Literature states RMSSD to be the most appropriate HRV measure in this case, because it can already be accurately determined from a time interval of 30 seconds. In order to calculate RMSSD, peak detections needs to be done on the heart rate data.

To determine anxiety levels from heart rate variability measures, a link needs to be formed. From literature follows that a lowered HRV indicates a higher anxiety level. This theoretic link is used to determine anxiety levels from HRV measures in this project.

After the anxiety levels are determined, feedback needs to be created to signal to the user. The most appropriate feedback modality within the context of track and field seems to be visual feedback, but this is not a proven fact. Based on personal experience and preferences of female competitive track and field athletes, it is concluded that all feedback modalities could be appropriate, as long as they do not distract too much. For this project, visual feedback is chosen because it does not distract much. Current applications that provide feedback on emotions also use colors, usually signaling low stress or positive emotions with green and blue colors and intense, negative emotions with orange or red colors. It is therefore chosen to signal low anxiety levels with blue and green LEDs and increased anxiety levels with orange and red LEDs.

Chapter 9- Future work

This chapter covers recommendations to future work, meaning aspects of the project that could use improvement in the future. These include the use of another measurement setup for the acquisition of heart rate data, broad data set creation, the creation of real-time feedback and finally the creation of a functional prototype in the intended shape.

Use of other measurement setup

One of the aspects that will make a huge difference in the future would be the use of a different measurement setup for the measurements of HR data. In the current version of the project, ECG is measured using an Arduino Uno with an Olimex shield. This setup has various disadvantages. The first of these being that this setup is wired. This causes the setup to only be used whilst the measured person is sitting down or standing relatively still. As this project concerns data gathering in athletes, one can imagine that this measurement is not sufficient for this purpose. Another disadvantage of this measurement setup is that it measures raw ECG data. Because raw ECG data is very sensitive to noise and movement artifacts, filtering is required to get a useful signal. Within the scope of a Creative Technology graduation project, filtering physiological data is not ideal. If another measurement setup were to be used, a lot of time would be saved in the data acquiring process, leaving more time for the realisation of a functional prototype. A brand that offers devices that would be good for getting clean, filtered heart rate data to use for HRV calculations is Zephyr. They have multiple commercially available devices that allow for direct HRV measurements. These devices could unfortunately not be used for this project because they did not work. The timespan of this project did not allow for enough time to investigate the reasons here for, but this is something that could prove useful to investigate in the future.

Creating datasets covering the whole range of HR spectrum

With the current measurement setup, measurements could only be done in rest or whilst moving around slightly. This caused only a small piece of the HR spectrum to be measured. With the use of another measurement setup, the whole spectrum can be measured, from complete rest to the maximum heart rate. This allows for a better calculation of HRV measures when compared to the current project state. Better HRV measures calculations result in more accurate feedback provided to the user.

Creating real-time feedback system

Due to time limitations, a non-ideal measurement setup and programming difficulties, the current system does not provide real-time feedback to the user. With the user of a different measurement setup and improvements on the code of this project, it will most likely be able to provide real-time feedback to the user.

Creating a functional prototype in the intended shape

In Chapter 4, the ideation phase of this project was described. Requirements were formed and concepts were developed which were suited to fulfil the requirements. Due to time limitations, the final concept developed in this chapter could not be realised. The intended feedback that this concept displays is realised, namely visual feedback using LEDs. However, these LEDs are not incorporated into the intended concept of a water bottle with lights, but are simply shown directly connected to an Arduino Uno via a breadboard. To perform a more useful user evaluation and show the intended use of the prototype better, the feedback must be incorporated into a working concept.

Appendices

Appendix 1- Software

Software name	Version specification
Python software	Version 3.8.10 (64-bit)
MATLAB software	Version R2020a
Arduino IDE	Version 2.1.0
PuTTY	Release 0.74 (64-bit x86 Windows)

Appendix 2- Hardware

Hardware name	Hardware specification
Create Arduino kit (protokit)	Bought at STORES on 22-05-2023
Arduino Board	Arduino Uno, Arduino Leonardo
Potmeter 10KΩ Lineair slider	Variable Resistor
Potmeter 10KΩ Lineair metal	Variable Resistor
LED 3mm	Green, Blue, Yellow, Red
Olimex EKG-EMG shield	

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