Non-intrusive patient monitoring for pressure ulcer prevention

Group F - Test Group

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Momo Medical

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by

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This thesis is confidential and cannot be made public until June 19, 2022.

TU Delft

Executive summary

Problem Definition
This bachelor final project was an assignment given by the start up Momo Medical named: "Improving health care with technology". This project was to use their existing technology and ideas to create a system to prevent pressure ulcers. Pressure ulcer are the medical condition that happens when a patient is left too long in the same position in bed. In order to combat this the nurses turn the patient onto a new posture every 3 to 4 hours. To improve upon this Momo Medical decided to built a sensor pad that has to be placed under the mattress in order to track the patients bed posture and to alarm the nurses when a patient has been on a side too long. The project group was divided into three parts: the sensor group who would look at the sensor pad, the algorithm group who would use the data from the sensor pad to determine the bed posture and the test group that had to built a system that could verify the algorithm. This report will talk about the test group. Based upon the data that Momo Medical acquired it was also possible to acquire the heart rate and the respiratory rate from the sensor data. A way to acquire this data was also looked at. The design requirement that were set were 95% accuracy for bed posture and 90% for respiratory rate and heart rate.

Design Description
In order achieve these requirements a few different types of reference signals were looked at that could be used in order to detect the bed posture, respiratory rate and heart rate. In the end an accelerometer and an commercial grade ECG chest strap were chosen. The accelerometer could measure the patients orientation and thus his bed posture. When the accelerometer is attached to the chest it is also able to measure the chest compressing as a result of breathing. The ECG chest strap was chosen as this gave a good platform upon which the accelerometer and the micro controller could be attached.

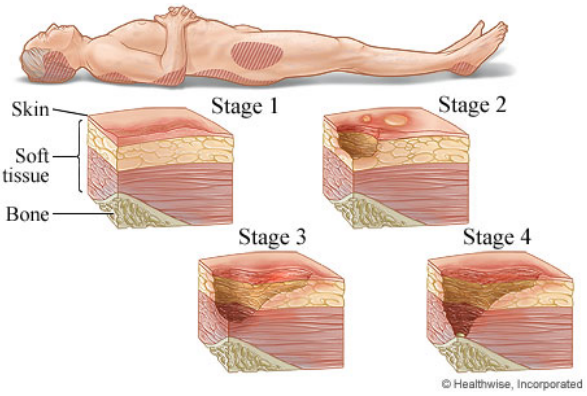
Evaluation
A prototype was built upon our design and it was tested in different situations. In the end the accuracy for the bed posture detection was 99%, the accuracy of the respiratory rate was 91% and of the heart rate it was 95%. With these accuracies it meant that the design requirements were met. The disadvantage was that the system influences the sensor pad while the patient is wearing the prototype. Another disadvantage was that due to the low sampling speed it was not possible to attach the heart rate receiver to the testing group's prototype, but had to be attached to the sensor group's prototype. These two disadvantages could be improved in the future by making the prototype smaller and faster.

Contents

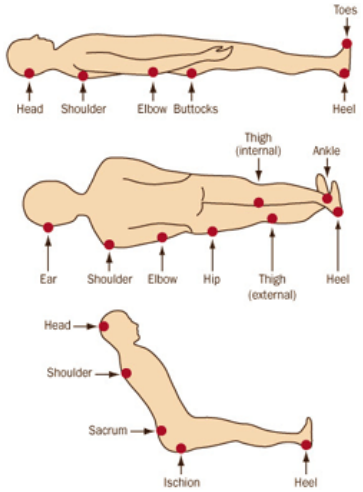
1 Problem Definition

1.1. Problem Scope

Pressure ulcers (also known as bedsores, or medically as decubitus ulcers) are a medical condition that affects patients worldwide. By sitting or laying with the same posture for an extended period of time (two or more hours, depending on the health condition of the patient), pressure ulcers start forming on the skin layer. If these ulcers are left untreated, the pressure ulcer wound expands to the soft tissue layer (see figure 1.1a). Particularly, the pressure points, as indicated in figure 1.1b, are susceptible to formation of such chronic wounds.



(a) The four stages of pressure ulcers [1].



(b) Sensative pressure points are indicated with a red dot [2].

Figure 1.1: The formation of pressure ulcers.

In the Netherlands alone, it is estimated that the treatment of pressure ulcers costs between 362 million to 2.8 billion U.S. dollar every years, which is around one percent of the Dutch health care budget [3]. This problem also plagues the United Kingdom, where, according to Posnett and Franks(2008), one in five British hospital patients are estimated to have had pressure ulcers [4].

Despite training of hospital staff in pressure ulcer prevention, the problem continues to affect patients worldwide, mainly due to lack of time and manpower of nurses [5]. This information makes clear that, a solution needs to be found for this problem.

1.2. Technical Review

The problem scope provided a short overview of the effects of pressure ulcers. This part focuses on the causes and the state of the art concerning the prevention of pressure ulcers.

1.2.1. Background of the field

Pressure ulcers are caused by many factors. This project focuses on three factors related to forces, that are exposed t the skin. The first factor is pressure. Continuous pressure on the same place of the skin cuts off the blood vessels and decreasing the oxygen and nutrient supply to the cells under the skin, which is damaging to the cells and increases the chance of formation of pressure ulcers. Pressure is the main reason that patients who are immobilized or can not move very well without help get pressure ulcers. The second factor is friction. Friction between the skin and the patient's clothes or bedding damages the skin and can cause pressure ulcers. The last factor is shear. This occurs when the skin moves in an opposite direction compared to the underlying bone or muscle tissue. This may cause stretching and even breaking of cells and blood vessels [6].

There are several positions that can minimize pressure while lying down [7]. In case patients are lying on their back, they should lie flat on their back or preferably lie in a 30 degree Semi-Fowler Position (see figure 1.2). Pressure and friction will be minimized in this position. In case the patients are lying on their sides they should preferably lie in a 30 degree lateral tilt position (see figure 1.3). This technique involves turning a patient to his/her side, and placing supportive pillows behind their back. Although this technique is simple, it is very effective, though time-consuming for nursing staff at the same time.

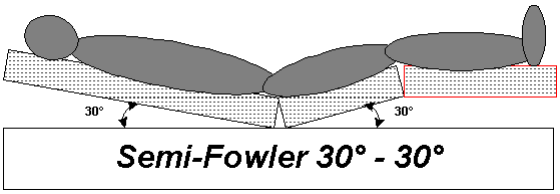


Figure 1.2: 30 degree Semi-Fowler Position [7].

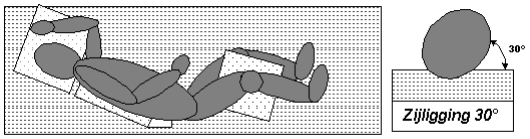


Figure 1.3: 30 degree lateral tilt Position [7].

1.2.2. State-of-the-art analysis

The technique for preventing pressure ulcers is basically very simple; by turning the patient regularly (for example, every four hours [8]) from one position to another, the active pressure points are shifted, thus preventing pressure ulcer forming. This is called *wisselligging* in Dutch. As it currently stands, this is the most common preventive measure [9]. In practice however, turning every patient individually at the hospital ward is a time-consuming task. Continuous tracking of the patient's body position can offer a technical solution for preventing pressure ulcers. With tracking information, the patient only needs to be turned around if the patient did not turn by himself. As a result, the patient would not need to be disturbed by unnecessary routine shifts and is much better protected from pressure ulcers [10]. One of these tracking systems is the BodiTrak [11]. This is a mattress cover containing thousands of pressure sensors that create a heat map of the pressure distribution. Pressure sensor mats which consist of an array of flexible force sensors [12] and continuous pressure mapping devices [13] are similar technical solutions, specifically developed and deployed to support pressure ulcer prevention. While very effective in tracking the patient's body position, they are very expensive, up to several thousands of euros.

Besides these mattress covers, also contact-free solutions exist, such as a system with a few piezo sensors placed beneath the mattress. Although not specifically developed for preventing pressure ulcers, such a system is capable of tracking patient's body position [14]. However, this system is also very expensive. Another system consists of high-resolution force sensors at each of the four bedposts [15]. This system is not ideal to use in a hospital setting where the beds have to be mobile. A solution is to build these sensors inside the bed frame, which would require hospitals to replace beds, a very expensive operation.

1.3. Project overview

This final bachelor project is an assignment given by the startup Momo Medical to use their existing ideas and technology to create a device that lowers the incidence of pressure ulcers due to continuous pressure in hospitals and other care institutions. During this final bachelor project the group was divided into three subgroups.

1. Sensors:
   The creation of a non-intrusive position monitoring system that collects data of the patient in the bed.
2. Algorithm:
   A piece of software that can determine the posture of the patient in bed using the data obtained by the sensors.
3. Test setup:
   A system able to verify the results of the algorithm group with a high degree of accuracy.

The global overview of the project is shown in figure 1.4, this diagram illustrates the different parts. It also shows the areas where cooperation between the different groups is required. In this thesis report the focus will be on the test setup group. In particular the design process and the choices that were made during to project will be looked at in detail. The final testing setup and results will also be discussed.

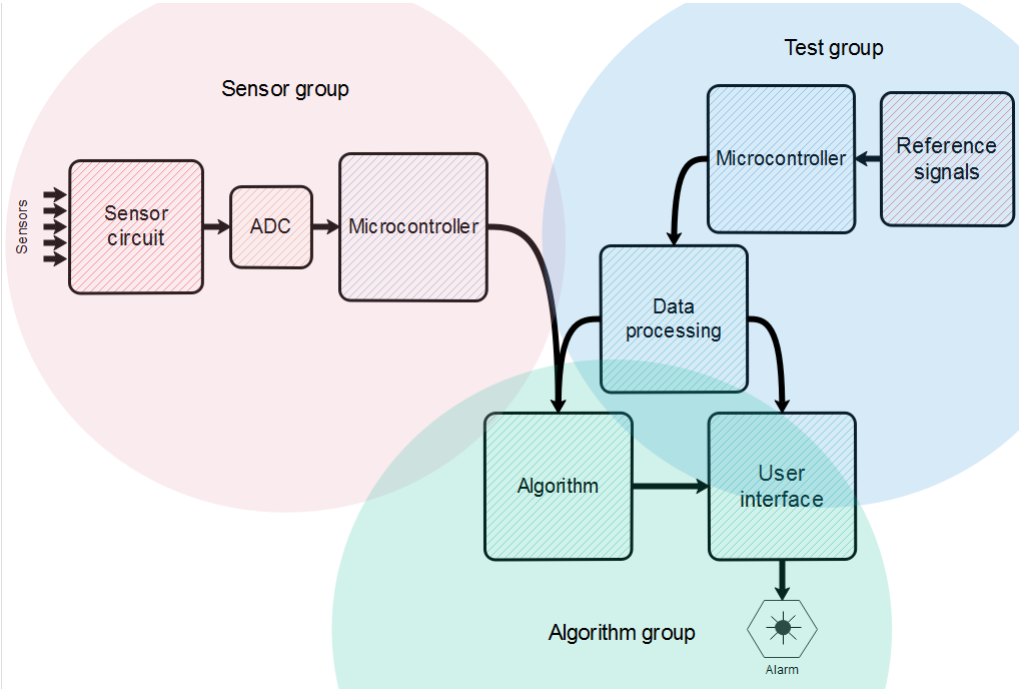


Figure 1.4: Project overview diagram

1.4. Design Requirements

Based on the ideas and assumptions obtained from the supervisor from Momo Medical, it could be determined that is possible to obtain the bed posture, the respiratory rate and heart rate of a patient by means of pressure sensors under the mattress. In order to verify an algorithm that can calculated these signals the following design requirements were set:

1. Bed posture and activity:
   This system must be able to determine the bed posture of a patient and the changes of posture over time with an accuracy of 95% or more. The reason that this accuracy must be so high is because this system directly relates to pressure ulcer prevention. To prevent pressure ulcers, the posture and activity of the patient must be known. The system must also be able to compare its result with the result obtained from the algorithm created by the algorithm group and with this determine the accuracy of the

algorithm. This is the primary design requirement. This is the main requirement that has to be met in order to decrease the incidence of pressure ulcers.

2. Respiratory rate:
   The system must be able to determine the respiratory rate of a patient with an accuracy of 90% or more. It must also be able to compare this result with the results obtained from the algorithm created by the algorithm group and with this determine the accuracy of the algorithm. The accuracy of this system still needs to be quite high, since it's a reference signal, however this functionality is of less importance compared to bed posture detection. The system must also be able to measure the respiratory rate independent of patient posture and activity. Measuring respiratory rate is a secondary requirement as it isn't needed in pressure ulcer prevention. Instead it gives the hospital staff valuable extra information about their patients, increasing the diseases that can be monitored.

3. Heart rate:
   The requirements for heart rate measurement are very similar to the respiratory rate measurements. The system must be able to determine the heart rate of a patient with an accuracy of 90% or more. It must also be able to compare this result with the results obtained from the algorithm created by the algorithm group and with this determine the accuracy of the algorithm. The accuracy of this system still needs to be quite high, since it's a reference signal, however this functionality is of less importance compared to bed posture detection. The system must also be able to measure the heart rate independent of patient posture and activity. Heart rate is also a secondary requirement as it isn't needed in pressure ulcer prevention. Instead it gives the hospital staff valuable extra information about their patients, increasing the diseases that can be monitored.

4. Physical design:
   The product created based on the previous requirements must be completely wireless, to be able to be setup within 5 minutes for quick testing purposes, reusable, non-invasive for the test subject and doesn't influence the sensors under the mattress. Finally, the design must not be too uncomfortable for the test subject in case it's a wearable device. This means that the subject must be able to wear it for at least an hour of testing. The physical design is the tertiary requirement as these parameters do not add any functions that have any medical value compared to posture, respiratory rate and heart rate. The complete design of the testing group should also not be too expensive. A budget of around 500 euro is allowed, though costs should be minimized as much as possible.

2

Design Description

This chapter will talk in detail about how the final design of the reference signals is realized. In the first section 2.1 a brief overview is given about the final design with a sketch. In section 2.2.1 the different choices of reference signals will be discussed and chosen in section 2.2.2. In section 2.2.3 a detailed description will be given about the current design. Finally, section 2.3 contains a short explanation about how the final design is used.

2.1. Overview

In figure 2.1 a sketch is given of the final physical design, which incorporates the choices made from the reference signals in sections 2.2.1 and 2.2.2. The top sketch is a top-down view of the design, and the bottom sketch is a side-view. The underside of the side-view is the wearer's torso, meaning the micro-controller and USB battery pack is sticking out from the body. The design is a band with an elastic strap that goes around the torso. The middle of the strap is worn above where the wearer's heart is and contains the heart rate monitor. The micro-controller responsible for sending measurement data to the computer encased in a plastic pack is attached above the heart rate monitor. The 5V USB battery pack powering the micro-controller is attached next to it. The inertial measurement unit (IMU) that is responsible for posture detection is encased together with the micro-controller in the plastic pack.

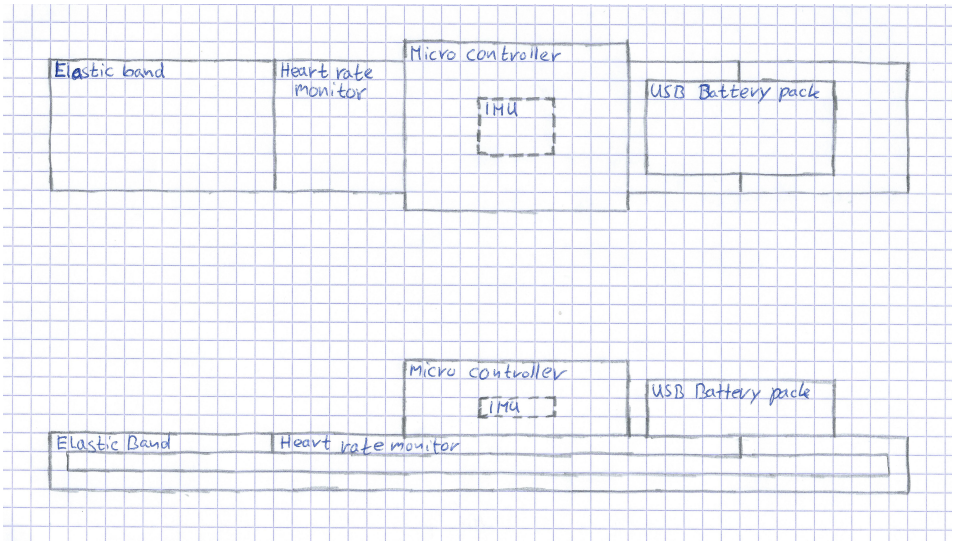


Figure 2.1: Sketch of the sensor design.

2.2. Detailed Description

The following section 2.2.1 will go into detail which options were considered in the design process. In section 2.2.2 the chosen methods will be discussed. In section 2.2.3 a description will be given about each chosen reference signal and how they are implemented in the whole system.

2.2.1. Reference Signals

For the testing of the sensors of the sensor group and the algorithm of the algorithm group it is important to carefully select which reference signals to include in the testing system. They need to meet the requirements as stated in section 1.4.

Before deciding which reference signal to select for the test setup, it is important to clarify what kind of output signal is expected from each reference signal. For bed posture the main idea is knowing on what side the subject is lying on. Either their back, left side, right side or stomach. Whether the patient is lying in a 30 degree lateral tilt position (see figure 1.3) is also important to know. For heart rate it suffices to know the beats per minute and for respiratory rate it suffices to know the breaths per minute. Both can be abbreviated to bpm.

Bed posture and activity

There have been many different studies for automatically detecting the bed posture and activity of a person, often for the purpose of sleep research or prevention of pressure ulcers. Not all studies are based on the same methods and not every method is applicable for use in this project. The following few paragraphs will discuss various methods for measuring bed posture and activity.

The first method considered is based on optical evaluation [16][17]. This means that this method utilizes one or more cameras to assess the patient's posture. Real-time image acquisition and processing is used to detect the optical flow of a patient. Optical flow is the apparent motion that arises from the relative motion between an observer and the observed object. There are different methods to detect optical flow, such as gradient-based, correlation-based, energy-based and phase-based methods [16]. A big advantage to using camera's and automatic image processing is that it requires no contact with the patient, meaning it will not impede the patient's activity while asleep. The images also give good visual feedback to manually determine at any point in time if the automatic image processing part of the system works. A disadvantage in the use of cameras however is that not everyone is comfortable with being filmed. This could limit the amount of patients willing to participate or it could hamper their sleep schedule. This is however less of a problem in this project, since tests will not be done on random patients, but on team members who are already willing to be test subjects.

Another method for sensor data validation is the use of similar sensors as the sensors made by the sensor group. [15] describes a method of using four high-resolution force sensors installed one under each bedpost. The advantage of using these sensors compared to a camera is that the patient will have no negative impact on their sleep schedule. This is because these sensors can hardly be noticed while sleeping. This method however comes with a few disadvantages. For one it lacks the manual feedback like cameras can provide to easily verify if the incoming data is true or not. Since the number of sensors used is so low, the accuracy of the sensors is hard to determine. Accuracy is an especially important factor in the case of reference signals, so this method may not be entirely suited as a reference.

Instead of only using four sensors as reference, another option is using a lot of pressure sensors instead [18][19]. Pressure mapping systems like BodiTrak often consist of hundreds if not thousands of pressure sensor points and are commercially available [11]. A big advantage of using pressure mapping systems compared to using only few sensors is the increased accuracy when using more sensors. In the case of a commercially bought mat it is also easier to use, since they are not generally designed for specific use by engineers. A disadvantage of using such commercially available pressure mats is the increased cost. These systems generally cost into the thousands of euros, which is not a budget that is available during this project.

Other than using pressure sensors or imaging techniques, it is also possible to use temperature as a way to detect body movement and in turn posture. [20] uses sixteen thermistors in a straight-line configuration. Changes in posture and body movement can be recognized by a change in temperature profile. While the accuracy of this system seems to be promising, the location of the sensors can be a problem. This is because

the line configuration is very close to the location of the pressure sensors of the sensor group, most likely within 15 cm of each other. The reference signals must not interfere with the signals they are validating, so either another location must be chosen for the thermistors or this option is to be discarded.

Similar to pressure mapping systems and temperature sensor configurations, [21] proposes another method which involves placing sensors in a certain configuration on or under the mattress. This time bed postures are recognized by using mutual capacitance sensing, comparable to the way capacitive touchscreens work. A grid of crossed wire electrodes is placed on top of the mattress. A change in posture will change the local electric field in the individual points, which changes the mutual capacitance. This change in capacitance in the individual intersections can be used to determine the posture of the person lying on top of them. An advantage of this method is that it is easy to deploy and is inexpensive to produce. A big disadvantage however is that resulting measurements greatly depend on the weight of the subject. In turn the accuracy greatly suffers from this. Test subjects of different body sizes result in an accuracy of only 80.76%. Since the required accuracy for the reference signals of this project need to be higher, around 95%, this method will not be suitable.

Rather than using a non-wearable solution like a camera or a pressure mapping system, there is also the option to use a wearable solution. This comes in the form using a wearable accelerometer around a subject's torso. With the accelerometer it is possible to calculate the roll angle of the subject and therefore their bed posture. An advantage to this method is that it is easier to implement than other solutions, since it only requires a simple calculation. It is also a lot cheaper, with many small inertial measurement units (IMUs) costing in the tens of euros. A disadvantage to this method however is that it is wearable, meaning it could have an effect on the results of the sensor group. It could also be uncomfortable for the test subjects to wear, so the design should be small enough.

It's not necessary to stick to only one method. In [22] a multimodal method is proposed. This method uses both video imaging and a pressure mapping system to classify sleeping posture. This combined system results in higher accuracy than using a single modal approach. This system has the added advantage of making it possible to manually check if the calculated posture is correct by using the camera images.

Respiratory rate

The measuring of the respiratory rate of a patient can be an important factor. An abnormal respiratory rate can for example me an important marker of a serious illness[23]. The following few paragraphs will note various ways of measuring respiratory rate. Some are contact based, while others are non contact methods. The advantages and disadvantages of these methods will also be discussed.

The first method describes an optical solution to detect respiratory rate and is also described in the previous section about measuring bed posture [16][17]. It uses optical flow to detect movement of the blanket when the patient is breathing. An advantage to this method is that it is a non contact way of measuring. A disadvantage however is that it requires the patient not to change bed posture. During this change it is temporarily impossible to detect respiratory rate.

Another non contact method is the use of pressure sensors under the bedposts[15] or under the sheets of a hospital bed[24]. This method is similar to the way this project is planning to measure the respiratory rate, since it is also based on pressure sensors. This means that this option may not be the best as a reference signal, since the accuracy is expected to be the same as the accuracy of the sensors of the sensor group. Higher accuracy is to be expected from reference signals and while contact-free measuring is an advantage, it is not a design requirement for the reference signals. This method also has the same disadvantage as the optical solution, meaning that movement will temporarily disrupt the ability to detect respiratory rate.

In [25] and [26] reflections are used to detect the respiratory rate, light and sound respectively. These non contact methods use the reflections of a sound wave or a light beam to calculate the distance between the transmitter and the chest area of the test subject in order to detect the respiratory rate of the patient. These distance depend on the chest compression that happens during breathing, increasing when breathing in and decreasing when breathing out. This method unfortunately is hard to use because the transmitter is pointed at the chest area and thus when the test subject moves from back to side or stomach the transmitter has to move with it. This makes the stomach posture hard to measure. On the other hand as long as the transmitter

rotates with the body the reference signal will not be disrupted. The method using light has an accuracy of 95% and the method with sound has an accuracy of 93% which means that they met the respiratory rate design requirement of this project.

Similar to the bed posture an accelerometer attached to the chest could also measure the respiratory rate of the patient as it detects the chest compression's caused by breathing. This is done by calculating the patients pitch and how it changes over time. This results in a sine wave which signifies the patients breathing on top of the patient pitch. This means that if the sample frequency is high enough the patients movements will not disrupt the ability to detect respiratory rate of the patient. Contrary to above methods, this method is contact based meaning it requires the patient to wear it. This could be a disadvantage since it might be uncomfortable to wear.

Heart rate

There are a lot of different options for heart rate monitoring. Options range from very accurate electrocardiography (ECG) to small and wearable heart rate monitors for use during physical exercise. There have also been various studies in non-wearable and contact-free methods of heart rate monitoring. The next few paragraphs will discuss these various options and their advantages and disadvantages.

The first method discusses the use of pressure sensors to detect heart rate, placed either under the bedposts[15] or under the sheets of a hospital bed[24]. This method is similar to the way this project is planning to measure heart rate, since it is also based on pressure sensors. This means that this option may not be the best as a reference signal, since the accuracy is expected to be the same as the accuracy of the sensors of the sensor group. Higher accuracy is to be expected from reference signals and while contact-free measuring is an advantage, it is not a design requirement for the reference signals. Another problem with this method is that it requires that the patient moves very little while laying down. Movement of the patient will temporarily disturb the heart rate measurements. Since a design requirement of this project is that the heart rate must be able to be measured independent of patient posture or activity, this method is not suitable for this project as a reference signal.

Instead of using a contact-free method for heart rate measurement, a wearable solution might be more suitable in this project for more accuracy. There are multiple studies which discusses different ways to measure heart rate. There is one that focuses on a wearable ECG method[27] and another one that uses a combination of acoustic and optical sensors[28]. Designing a wearable ECG might however be too high performance and therefore unnecessary for the type of application required in this project. The only information needed in this aspect of the project is the heart rate. Specific information about the electrical activity of the heart is not needed. The use of either acoustic or optical sensors or a combination of both might therefore be a better solution. Acoustic sensors are similar to a stethoscope in that they measure heart rate with sound. They do not need to be in direct contact with skin. Optical sensors do however need to be in direct contact with skin and use light to measure blood flow to calculate heart rate. Using a combination of both will have the advantage of improving accuracy by using multiple references.

There is also the option of using a commercially available way of measuring heart rate. This can be done by using a chest strap, which contains electrode pads and function like an ECG. Which uses electrodes attached to the chest to measure the electrical potential of the nerves around the heart in order to detects the heart beat. The chest strap on the other hand only detects the peak of the QRS-complex of the heart beat in order to determine the heart rate. The QRS-complex is the most central and highest peak of a typical ECG wave. Another option is using a wrist heart rate monitor, which functions optically. The advantage to this method is that it is easier to implement compared to designing such a system personally. Another advantage is that accuracy is often guaranteed by the manufacturer. A disadvantage with using commercially available devices is that it might be more expensive than designing one personally. Such heart rate monitors cost however often under hundred euros, meaning it is within budget of this project.

2.2.2. Design Choices

Bed posture and respiratory rate

As reference signal for both the bed posture and respiratory rate an IMU was chosen as this component is able to measure the orientation of the patient whose its attached to. When such an IMU is attached to the

chest of the patient it becomes possible to use it to measure the chest compressing and decompressing that are a result of breathing in and out. With both the orientation and the chest movement of a patient it is reasonable to use an IMU in order to determine both the bed posture and the respiratory rate. Commercially available pressure mats were also looked at as it is also possible to use these to determine the bed posture and respiratory rate. This is done by using the pressure distribution and center of gravity. These pressure mats are however outside the budget for this project as the cheapest of these mats cost around 2000 euros.

Camera

For redundancy a webcam was added to the test setup. This was done in order to document the cases where the results of the algorithm and the test system are not the same in order to make it possible to visually check what went wrong in those cases. This webcam also had two requirement that had to be met. The first one was a night vision function because this gives the option to test sleeping postures during an entire night without interfering by leaving the lights on. The second requirement was that the webcam was wireless in order for easier placement and as part of the physical design requirement.

Heart rate

A commercially available ECG heart chest band was chosen as reference signal as this gives a reliable reference signal that can be monitored wirelessy. It is also a suitable platform to attach with the other components like the IMU around the chest of the patient.

Micro-controller

For the controller of the design a raspberry pi was chosen as this had a Matlab hardware support package and contained a built-in I2C bus and SPI connection. With these connections it was possible to attach all kinds of sensor packages. The raspberry pi is a complete Linux computer and therefore also contained the latest security and internet protocols making it more secure than other micro controllers. During this decision was also looked at FPGA development boards, but in the end this option was not chosen. In order to connect it to anything the required module has to be either found on the internet or written manually. This makes it harder to built a prototype and thus due to limited project time this wasn't chosen.

2.2.3. Implementation

In Figure 2.2 the design layout is shown. The IMU is in this case attached to the raspberry pi via the I2C bus. While the raspberry pi is connected to the computer wirelessly by making use of the Matlab hardware support package. The receiver of the heart band was in this case not attached to the raspberry pi in order to get the data on the computer. It is instead attached to the micro controller used by the sensor group via a digital pin. The micro controller itself was attached to the computer via a USB cable. During testing it was found out that the raspberry pi used via Matlab did not have a sampling frequency high enough in order to sample the heart rate. The micro controller has a higher possible sample frequency of 100 Hz while the raspberry pi in combination with Matlab only has a maximum sample frequency of 7 Hz. This sample frequency was too low to detect the 60-100 ms pulses that are the QRS-complex of the heart beat that an ECG hard band detects. These pulses would have needed a sampling frequency of at least 10-16.67 Hz. The webcam on the other hand was attached to the computer via the wireless network.

In order to use the acceleration values that are gotten from the IMU the following formulas are used. For the roll of a patient equation 2.1 was used and for the pitch of the patient the equation 2.2. With these values the bed postures and the respiratory rate. An accelerometer measures the acceleration on an axis by measuring the displacement of a dampened mass as a result of the acceleration. This means that in order to detect the bed posture and respiratory rate 3 orthogonal axes were needed: the X, Y, Z-axis. The default output of an accelerometer in rest is 1g in the direction opposite of the earth's gravity. With this default output the bed posture and respiratory rate will be calculated using equation 2.1 and 2.2. The direction of The Z-axis is defined as pointing upwards with respect to the orientation of the IMU. The X-axis is pointing towards the patient's head and the Y-axis to the patient's right arm. The roll was used in order to determine bed posture by using Table 2.1. With 0° being that the IMU was at an horizontal orientation and thus the patient was in this case on his back. To determine the heart rate and the respiratory rate the fast Fourier transform was used and afterwards using the first peak in the spectrum in order to calculate the beats and breaths per minute. Another option within the time domain was to to count the time it takes for a certain amount of periods of the signal to occur and using this to calculate the bpms.

$$Roll = \frac{180 * tan^{-1}(\frac{Y}{Z})}{\pi} \tag{2.1}$$

$$Pitch = \frac{180 * tan^{-1}(\frac{X}{\sqrt{Z^2+Y^2}})}{\pi} \tag{2.2}$$

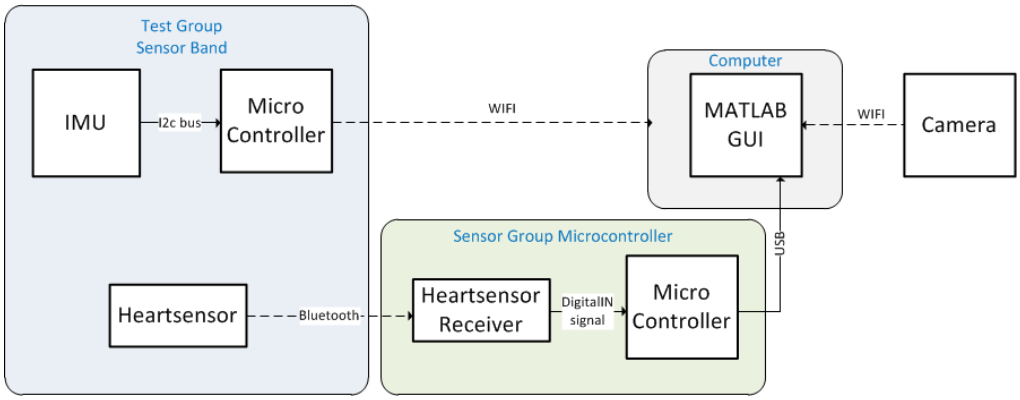


Figure 2.2: Overview of the complete testing system. Dotted lines are wireless. Solid lines are wired.

Table 2.1: Bed postures with their patient roll ranges.

Posture	Patient Roll(°)
Back	-30 < x < 30
Left side	30 < x < 150
Right side	-150 < x < -30
Stomach	150 < |x| < 180

2.3. Use

To use the IMU in Matlab first it is needed to connect to the raspberry pi. Afterwards the IMU must be accessed via the I2C bus in order to make it possible to retrieve the data. After this the previous equations could be used in order to calculate the pitch and roll of the patient. In the code example below can this be seen implemented with the IMU mpu6050.

```
testpi = raspi('192.168.1.103', 'pi', 'raspberry');
mpu = raspi.internal.mpu6050(testpi, 'i2c-1');

[x, y, z] = readAcceleration(mpu);
r = (180*(atan2(y, z)))/ pi;
p = (180*(atan2(x, sqrt(z^2 + y^2))))/ pi;
```

In order to acquire the results from the heart rate monitor it is necessary to connect the micro controller of the sensor group first and run the python file getserialtry.py which can be found in appendix B. Afterwards within matlab the code has to be imported and can be used directly. This code can be seen below.

```
filePath = 'C:/Users/Wim/Desktop/ML/Resistive_Output.csv';
testData = csvread(filePath);

heartRate = testData(:,10);
```

For the final element to access the webcam via Matlab in order to make screenshots the following code was necessary.

```
options = weboptions('Username','admin','Password','');

img = webread('http://192.168.1.105:10000/tmpfs/auto.jpg', options);
```

3

Evaluation

This chapter will talk in detail about the prototype that was built based on the design of the previous chapter. In section 3.1 a brief overview will be given on the prototype and the tests performed in order to verify the design. In section 3.2 a detailed explanation will be given on how the prototype was built from the design and which parts were used to achieve this. In section 3.3 the tests and their results will be described. In section 3.4 the conclusions about the data will be talked about and in the final section 3.5 will be talked about possible future improvements upon the design.

3.1. Overview

In order to verify if the design met the design requirements (see section 1.4) a prototype was built and a test setup was created. The prototype was created with the physical design requirements in mind. The prototype that was created was a wearable for the patient that the patient wears around their chest. This prototype makes it possible to monitor the patients posture, respiratory rate and heart rate. First was decided which situations were needed to be tested in order to validate the design requirements and based on this a test plan was designed. With the test plan it was decided which postures, position and pitch angle were looked at and how much measurements are performed for each test.

The test plan was divided into four parts. In the first part the different postures, position and angles were tested when the test subject was not moving when the measurements were taken. During these tests the posture, position and the other looked at values are manually selected in a GUI and later attached to their measurement in the data. With this data the static part of Bed posture design requirement was tested. In the second part the the heart rate was looked at. During this test the data was continuously recorded and an external heart rate and blood pressure measuring device was used in order to verify the data afterwards. This was needed in order to verify if the heart rate design requirement was met. In the third part the respiratory rate was tested. In this part the incoming data was also continuously measured and during this test the respiratory rate was kept track of by the test subjects themselves using a website designed for this[29]. This was done in order to verify if the respiratory rate design requirement was met. In the last part of the test the transitions and activity were measured. This test was also continuously recorded and during the test the postures and the position were digitally kept track of and added to the test data. With this data the dynamic part of Bed posture design requirement was tested. Afterwards a few small tests were performed in order to validate the physical design requirement. In Table 3.1 is a short summary visible.

These tests were also performed with the goal in mind to get test data for both the algorithm and the test group in order to verify their design. This resulted in the test results having both the data acquired from the sensor pad constructed by the sensor group and the data acquired from the prototype created by the test group. The result of acquiring the data of both systems at the same time serves the goal to make it possible to directly compare the results of both systems and make conclusions based on this.

Table 3.1: Design requirements and their test methods

Design requirements	Test method
Posture & activity	Using the postures back, sides, stomach and 30 degree lateral tilt and the positions middle, left and right of the bed and the head rest pitch of 0°, 30°and 45°in order to determine the accuracy of the test prototype.
Respiratory rate	Comparing the value gotten from the test prototype with an external system in order to verify the results and compare this with the algorithm group.
Heart rate	Comparing the value gotten from the test prototype with an external system in order to verify the results and compare this with the algorithm group.
Physical design	Performing physical tests on the prototype in order to verify if of the each sub-parts of the physical design requirement were met.

3.2. Prototype

In Figure 3.1 the prototype wearable based on the chosen designs is shown. In this figure the cover over the raspberry pi is detached in order to show the accelerometer inside the construction. In the prototype the raspberry pi 3 model 3 v1.2 was used as the controller of the system. This decision was based on the fact that this was the most advanced raspberry pi currently on the market that Matlab support in its hardware packages. Another reason for this decision was the integrated wireless internet module which is inline with the physical design requirements. For the wearable heart rate monitoring device the polar T34 transmitter was used as this one of the few devices the receiver was able to be ordered as an component and isn't built into a larger system or uses a smart phone app. In this case the receiver generates a 16 ms pulse upon each heart beat which means a sampling frequency is needed of at least 62.5 Hz in order to detect all the pulses. In order to measure this signal the sensor group decided to implement the sampling frequency of 67 Hz for their micro controller and with this the ECG heart band was successfully implemented. The accelerometer that was used within the prototype was the MPU6050 as this was the only accelerometer in Matlab that was supported in the hardware support package. The final component in the prototype which was visible was the USB battery pack that is used to power the raspberry pi in order to make the prototype completely wireless. What isn't visible in Figure 3.1 is the webcam that was also part of the test setup. For further details about the prototype look in appendix A.

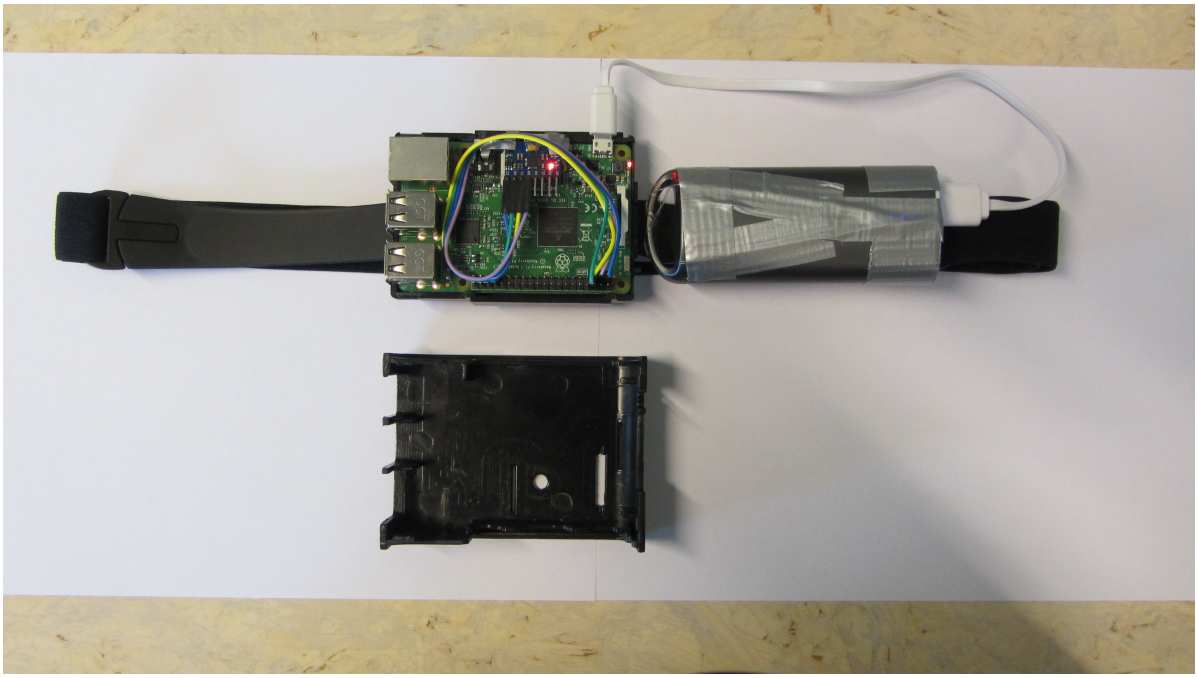


Figure 3.1: Prototype wearable without the cover.

3.3. Testing and Results

The test setup that was used is visible in Figure 3.2. In this sketch the positions of the wearable, the webcam and the sensor pad are visible. The hospital bed that was used was borrowed from the Reinier de Graaf hospital which was a partner of the company Momo Medical. With this test setup the tests will be performed for posture, respiratory and heart rate design requirements. For testing purposes a test GUI was built in order to facilitate the testing process. In appendix B a detailed description of the test GUI can be found and its source code. In appendix C all the unprocessed measurement of the test can be found including the way to interpret the data.

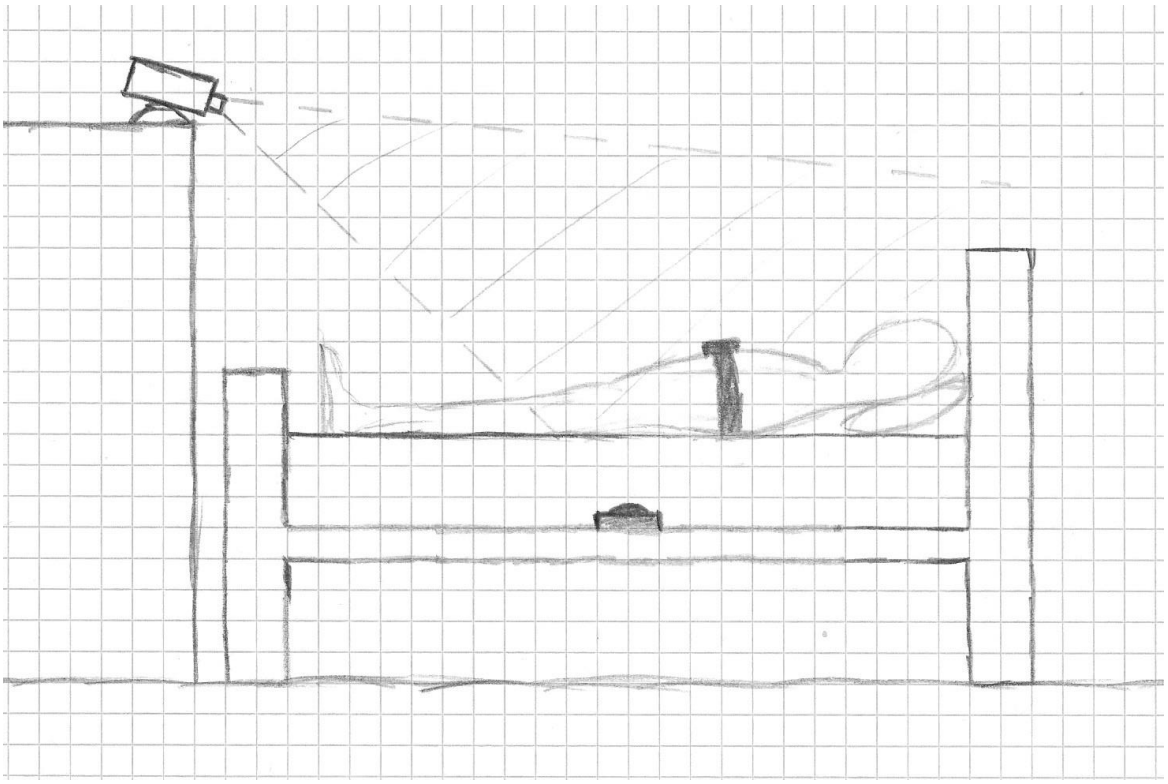


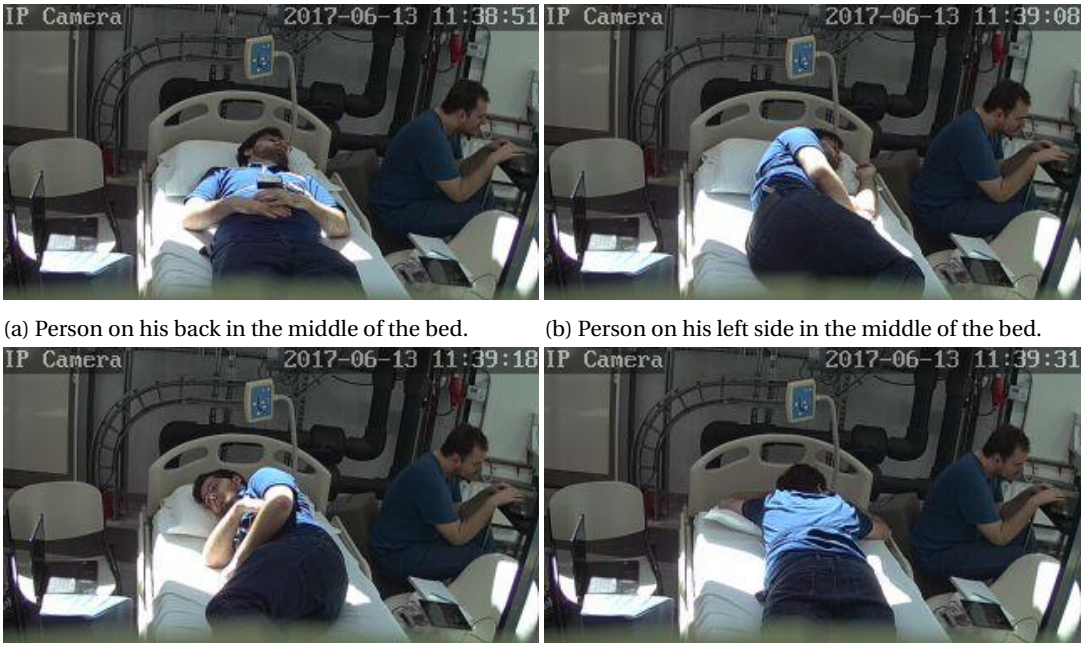
Figure 3.2: Sketch of test setup. The test group prototype was around test subject's chest , sensor group prototype under the mattress and a webcam to document some of the findings.

3.3.1. Bed Posture and Activity

This is the primary design requirement of this prototype because this determines its effectiveness in pressure ulcer prevention. This means that this design requirement has to be tested thoroughly and accurately. This requirement has a static part(bed posture) and an dynamic part(activity and transitions). The static part is necessary for the pressure ulcer prevention because this part makes long-term patient bed posture monitoring possible. While with the dynamic part it is harder to calculate the posture as it only contains changes, it is still possible. But this isn't the main use of the dynamic part. It is better to use these changes to determine the activity of a patient. This can be used to determine if the patient can stay longer in his current posture or not. With more activity the risk for pressure ulcers lowers and that makes it possible to stay longer in the same posture. This dynamic signal can also be used in order to determine when the patient stopped moving in order to determine the bed postures more accurately. The accuracy values that were obtained for the test group will be compared with the values acquired by the algorithm group to determine if the current test design is an effective manner to verify the algorithm and sensor pad. In the following sections the different test variables will be discussed.

Postures

The postures that were used during testing were: the back (Figure 3.3a), the left side (Figure 3.3b), the right side (Figure 3.3c) and the stomach (Figure 3.3d). These four postures are the posture that a patient themselves



(a) Person on his back in the middle of the bed.
(b) Person on his left side in the middle of the bed.
(c) person on his right side in the middle of the bed.
(d) Person on his stomach in the middle of the bed.

Figure 3.3: Measured bed postures

can get into, as long as he is not completely immobilized. The results from the test concerning these postures is therefore not only useful for hospital but also other care institutions, like home-care or retirement homes. For every posture assumed during the test ten samples were taken with an interval of 0.5s and this action was repeated 3 times for every different position that was assumed by every test subject. The test for the same posture will not be done directly after each other without moving. This was done in order to prevent the situation that when a test subject was in the incorrect posture. This would have a negative effect on the measurements in that posture. During the test the test subject wasn't moving around and thus there was no change during the sampling making the interval at which was tested irrelevant for all the bed posture tests and gave the option to freely choose this value. The value for the interval was chosen as 0.5s as this is above the restrictions placed upon the prototype by the connection between Matlab and the Raspberry pi. This gave a sampling frequency of 2 Hz. To determine the accuracy of the prototype the patient roll that was acquired during the test will be compared with the actual posture at that time that were added within the measurements.

Patient location

The next variable that was looked at was the position of the patient on the bed. This was looked at because patients will use the entire bed not only the middle. In order to see what the differences are between the different positions on the bed three positions were tested: the middle (Figure 3.3a), the left (Figure 3.4a) and the right (Figure 3.4b). These positions at the side of the bed were added because they represent the limit of the range of the bed and the sensor pad and thus give a different data set than the middle position. The accuracy for the different positions will be calculated separate from each other to determine if there is any influence on data from the edges of the bed.

Pitch Bed

Next the pitch of the head rest was looked at. For most of the hospital beds it is possible to change the angle of the headrest of the beds. The change in the pitch is also used in pressure ulcer prevention, for example 30° Semi-Fowler Position[7]. The angles that were tested were: 0° (Figure 3.3a), 30° (Figure 3.5a) and 45° (Figure 3.5b). It was decided that for the different angles only the middle position was looked at. For the 30° it was determined to not test the stomach posture as this was not possible because the spine can't bend that far back and this isn't a posture used in pressure ulcer prevention at that angle. In the case of 45° only the back position is looked at. Higher pitches weren't looked at because they aren't used in pressure ulcer prevention.

(a) Person on his back on the left side of the bed.

(b) Person on his back on the right side of the bed.

Figure 3.4: Measured positions

(a) Hospital bed with the head rest at an angle of 30°.

(b) Hospital bed with the head rest at an angle of 45°.

Figure 3.5: Measured pitch angles

They also increase the incidence of pressure ulcer because of the increase in pressure on the lower torso and the increase of shear force on the body.

Repositioning

Two extra posture that were looked at were the 30° lateral tilt postures(Figure 3.6a and 3.6b) as this is frequently used in pressure ulcer prevention[7]. These posture were only measured in the middle of the bed with a pitch of the head rest at 0° as only in this situation is this posture used. To use this posture an extra pillow is needed in order to place the torso at a 30° angle. This is to relieve the pressure on parts of the torso. While this pillow might not haven an effect on the measurements done by the test prototype it will create an unique pattern on data acquired by the sensor pad making this position a valuable addition.

Transition of postures

The transition of postures will be measured in a different manner as the previous test variables as in this case we use the continuous mode to record the measurements. This means while the raspberry pi will still be sampled at an rate of 2 Hz the micro controller of the sensor pad will be sampled at 67 Hz. With this increase

(a) Person on his left side in a 30° lateral tilt posture.

(b) Person on his right side in a 30° lateral tilt posture.

Figure 3.6: Measured repositioning postures

in the amount of samples that were produced the transitions between the different postures becomes more detailed than the measurements done during the static part. During the test only in the middle of the bed will be tested. This gives the test subject more space to move around and reduce the risk of someone falling out of the hospital bed.

Control

In order to exclude the influence of the mattress in the measurements a control test was needed. This was tested in the situation that there is no test subject wearing the prototype and that there is no one on the bed in order to get a set of data without a person influence. With this data it is possible to correct any offset that the prototype has. The second control test is the situation that the test subject is on his stomach without the test prototype in order to see the influence the wearable has on the sensor pad.

Results

In Figure 3.7 the test results of all the postures in the middle of the bed are visible. In this Figure the patient roll during every posture is displayed. The accuracy of the wearable in this situation is 98.4%. In this Figure can be seen that some of the data points of the stomach posture are outside the expected value of this posture and thus are detected as left side instead. This difference can be explained as that the selected threshold values weren't correct and would need improvement. This can be seen in that if the threshold value would have been 120° instead of the current 150° the accuracy would become 100%. A second explanation would be that every test subject had differences in their stomach posture because it is an uncomfortable posture in and of itself when not used to it. In this case the addition of the wearable made it worse and thus influences the stomach measurements. This influence can be seen in the bigger spacing between data points in comparison with the other postures. Another explanation could be that the wearable was not completely centered which can be seen in that the data points for the back posture are all below zero while it would have been expected that the mean of these data points would be zero. In this case the main reason the accuracy isn't 100% is the offset and when this is taken into account will result in a 100% accuracy.

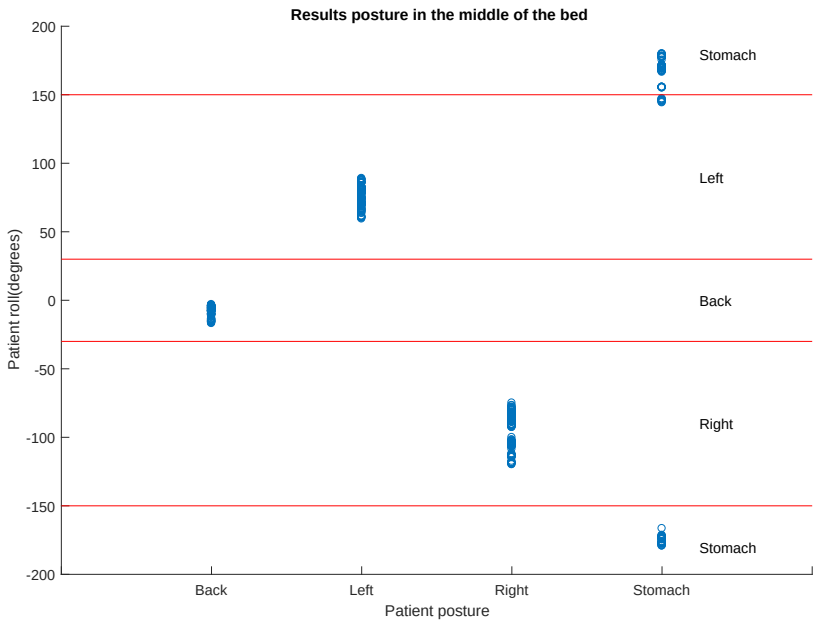


Figure 3.7: Graph showing the acquired results at the different postures in the middle of the bed, included are the threshold lines that were used to determine the posture based on the patient roll

In Figure 3.8 are the results of both the left and right side of the bed shown. In this case only on the left

side of the bed a few data points fall outside the assumptions while on the right side all the data points do not. This results in an accuracy of 99.5% and 100 % respectively. In this Figure the same argument can be made for the data points that are recognized wrongly as a different posture. In this case the difference between stomach posture between the test subjects is smaller which is seen as less spacing between the points than in Figure 3.7. These graphs also support the explanation that the wearable was off center because in these graphs the back postures mean is off center too. This means that for further test it is useful to define what the postures exactly are in order to decrease the differences between test subjects.

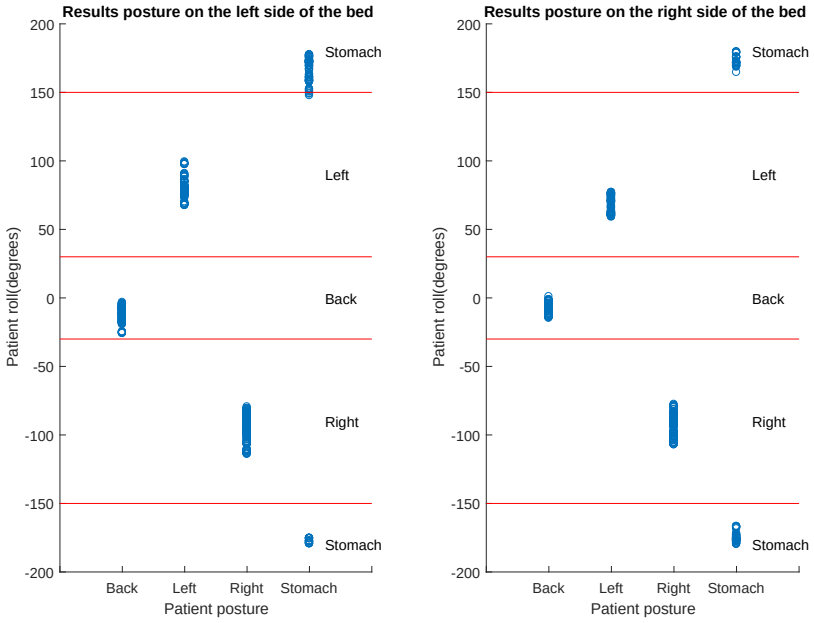


Figure 3.8: Graph showing the acquired results at the different postures on the sides of the bed, included are the threshold lines that were used to determine the posture based on the patient roll

In Figure 3.9 the results are shown for the two different angles that were tested. The accuracy at both angles is 100%. The main reason that this accuracy is 100% was that at both angles the stomach posture wasn't tested as this posture isn't used at these pitches. These are the data points that were sometimes recognized wrongly. In this graph it is also visible that the side postures are more inconsistent than at a 0° pitch which can be seen in Figure 3.7. This is because these posture are harder to perform at an elevated pitch.

In Figure 3.10 the results of the 30° lateral side postures are visible. With this Figure it becomes clear that the threshold values that were used to determine the posture are insufficient to determine these two postures as the resulting accuracy is only 73.3%. This could be the result that the posture wasn't done properly as none of the group member had the correct medical training to do this posture and thus this results in a greater variance in the results. The second reason could be that the threshold levels that were used should have been different as they do not take these postures into account. If for example if the upper limit of the threshold for the back posture was 10° instead on 30° the accuracy would have been 100% without influencing the accuracies that were calculated for the tests before. A final reason could be that the different weights of the test subjects could influence the roll angle that was measured. The pillow that was used could therefore compress more or less depending on the weight of the test subject.

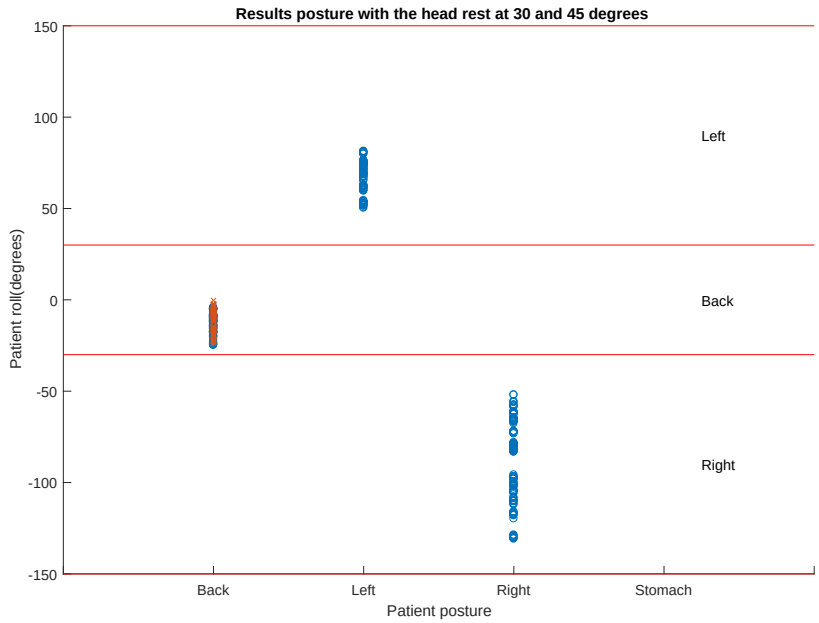


Figure 3.9: Graph showing the acquired results at the different postures at different inclinations of the head rest of the bed, included are the threshold lines that were used to determine the posture based on the patient roll. Blue is 30° and red is 45°.

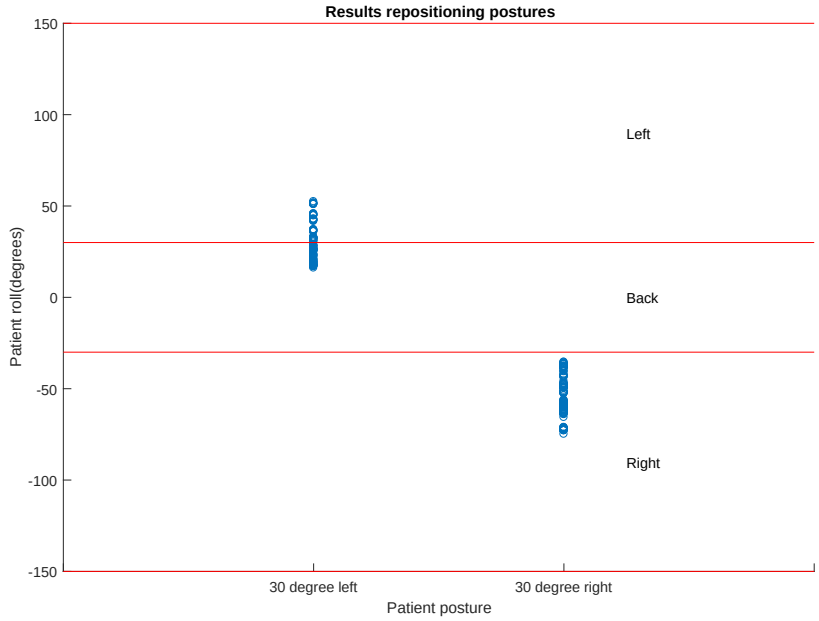


Figure 3.10: Graph showing the acquired results with the 30° lateral side posture in the middle of the bed.

In Figure 3.11 are different transitions displayed. Calculating the accuracy of this data set gives 78.1%. This is caused by the mistakes that are made during the transitions themselves as only the accuracy of the postures

is calculated and not the transitions themselves. This means the accuracy can be increased by removing the transitions or by increasing the amount of states the accuracy currently tests on which are all the postures excluding the 30° lateral side postures as they weren't used during this test.

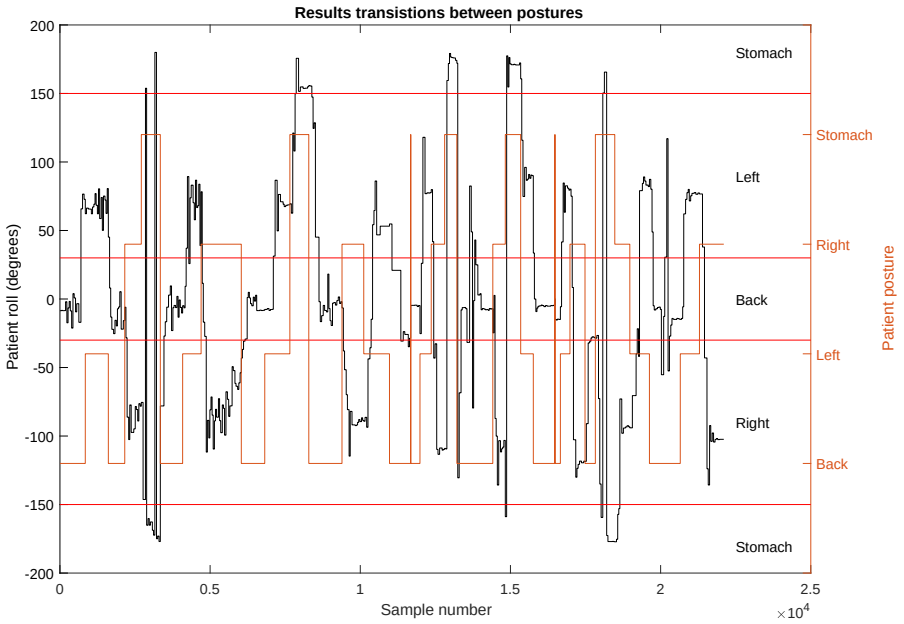


Figure 3.11: Graph showing the the transitions between postures with the black line being the patients roll and the orange line the posture of the patient

In Table 3.2 the control tests are visible. These value are the quantization levels of the ADCs that were used in the sensor pad. In this Table the influence of the mattress and the test prototype on the sensor pad are shown. Based on this Table it can be concluded that the test prototype has a significant effect on the sensor mat and thus does not meet that part of the physical design requirement when the test subject is on his stomach.

Table 3.2: Mean values of the quantization levels of the ADCs of the resistive sensors at different postures

Test situation	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5
No person on the bed	1884.2	1751.4	3218.6	2357.2	5721.1
Person on stomach in the middle	3153.8	4246.3	11024.0	5004.8	8658.8
Person on stomach without the wearable	4542.1	5056.7	6922.4	2508.3	8094.3

The bed posture and activity design requirement was met as the accuracies of the different tests were higher than 95% except the transitions and the 30° lateral side postures. The transitions do not have to be included based on the fact that the accuracy was not determined based on postures during the transitions. This was because it is impossible to constantly enter the correct posture during the transition themselves and thus giving a lower accuracy than actually achieved. The 30° lateral side postures are in this case excluded because the thresholds currently in use weren't optimized for these postures. The algorithm group implemented a system to check if a patient is on either his side or back while in the middle of the bed. In this situation the accuracy of the wearable is 100% as the stomach posture and the 30° lateral side posture weren't included as only those postures created inaccuracies in the results of the current prototype. The 100% accuracy is in this

case possible as there were not enough measurements performed, however the accuracy shall not be to far removed from the 100% if more measurements were to be taken. The algorithm had an average accuracy of 90% which is lower than the 100% that the test prototype had in a similar situation. This means that the test prototype is a valid system that can be used in order to verify the algorithm.

3.3.2. Respiratory Rate

This is the first secondary requirement that was tested. This signal was tested in continuous mode of the test GUI, like the transitions of the posture before. The sample frequency of 2 Hz of the raspberry pi is enough to measure the respiratory rate of the wearer because it fulfills the Nyquist criterion. According to the Nyquist criterion the sample frequency has to be at least twice the highest frequency occurring within the signal, $B_{sample} = 2B_{max}$. Because the average respiratory rate of adults is 12 - 20 breaths per minute[30] this gives a frequency of 0.20 to 0.33 Hz. The raspberry pi was able to measure this signal. A frequency of 0.4 to 0.66 Hz was needed for the signal to be measured as stated by the Nyquist criterion. For sampling a frequency of 2 Hz was used. The highest measurable data frequency would have been 1 Hz and that is three times the adult average. The external source that was used during this test in order to measure the respiratory rate was a respiratory tapper[29]. The test subject had to indicate when he was breathing in and when breathing out and with this the website calculated the average breaths per minute(bpm).

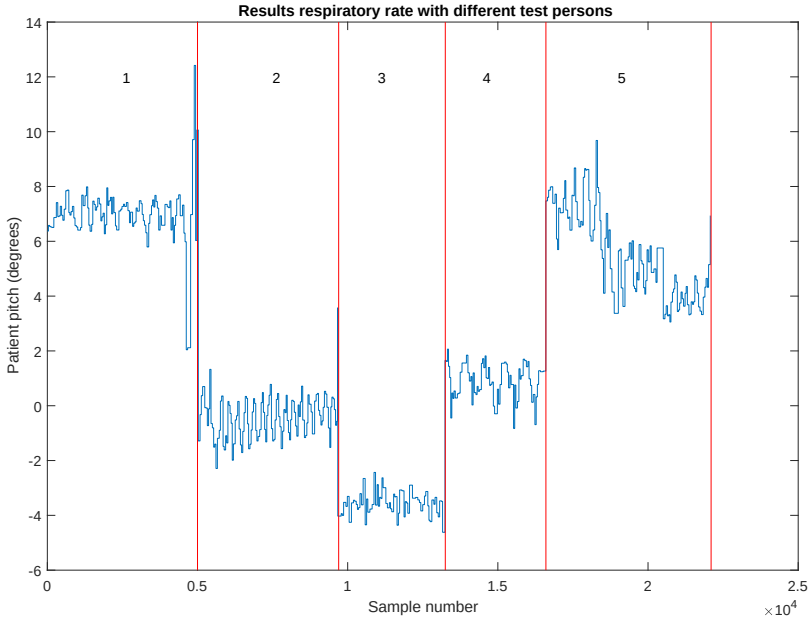


Figure 3.12: Graph showing the acquired patient pitch with the different test subject in order to display the respiratory rate. The numbers above indicate the different test subjects.

In Figure 3.12 and Table 3.3 the results of the measurements are shown of the respiratory rate tests. The values were calculated by using the Fourier transform on the measurements and afterwards using the first non-zero peak of the frequency spectrum to determine the respiratory rate, as seen in Figure 3.13. Using this method the accuracy of this part of the prototype is 91.44% as the average difference between source and measurement is 8.56%. With this the design requirement is met. The algorithm group failed to implement respiratory

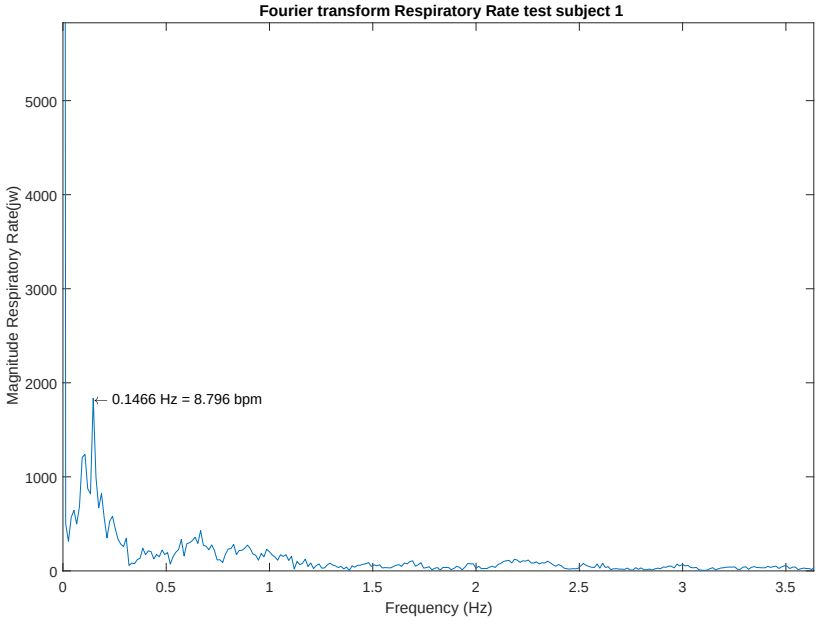


Figure 3.13: Fourier transform of the respiratory rate of test subject 1

Table 3.3: Respiratory rate that was calculated from the measured patient pitch compared with the value acquired by the external source.

test subject	External source(bpm)	Calculated value(bpm)	Difference
1	9	8.80	2.3%
2	15	15.16	1.1%
3	15.5	14.57	6.0%
4	7.4	5.97	19.8%
5	12.5	10.78	13.8%

rate detection because their priorities lied due to time constraints with the posture detection. With this it is impossible to determine if the test design is a valid system with which the algorithm can be verified.

3.3.3. Heart Rate

This is the second secondary requirement that was tested. This signal was also tested in continuous mode.The maximum heart rate of a human is around 220 bpm[31] which gives a frequency of 3.67 Hz. This means in order to sample this frequency a sample frequency of 7.33 Hz or higher is required. In this case this is not enough as the receiver generates 16 ms pulses upon each heart beat. This needs at least a sampling frequency 62.5 Hz. While 8 Hz is achievable on the raspberry pi 62.5 Hz isn't. This meant that the receiver could not be attached to the wearable and had to be attached to the micro controller of the sensor pad as this was using an sampling frequency of 67 Hz. The external source used in order to verify this signal was a digital blood pressure monitor, the Cresta HL 168A. This blood pressure device had a built in heart rate monitor with a deviance of maximum 5%. Three tests were performed because the blood pressure monitor can't monitor the heart rate continuously. Two times was the heart rate tested in the middle of the bed on the back posture in order to generate data for both the algorithm group and the test group. In the final test the heart rate is tested sitting as in this posture the blood pressure monitor has the highest accuracy.

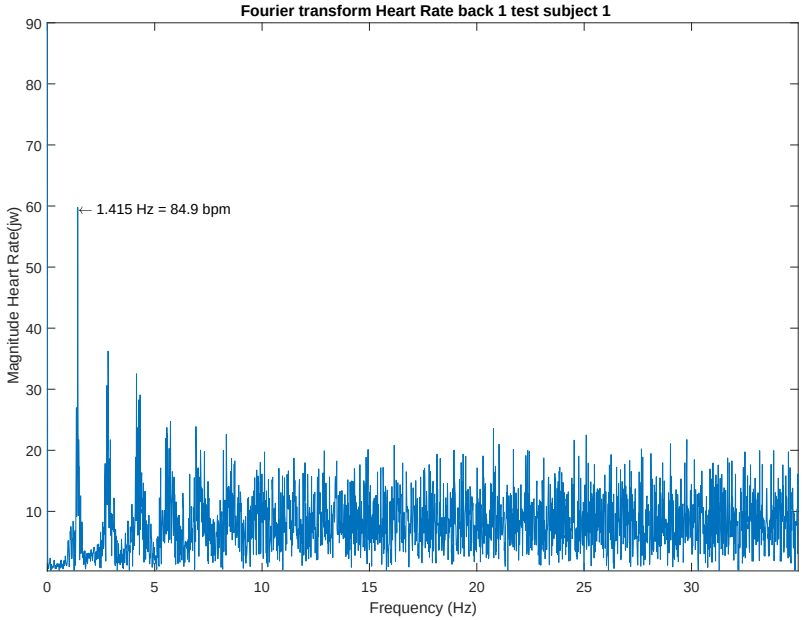


Figure 3.14: Fourier transform of the heart rate of test subject 1 on his back the first time

Table 3.4: Heart rate that was measured by the micro controller compared with the value acquired by the external source.

test subject	Posture	External source(bpm)	Calculated value(bpm)	Difference
1	back	82	85	3.6%
	back	75	81	8.0%
	sitting	80	81	0.7%
2	back	72	71	2.0%
	back	66	67	1.9%
	sitting	69	71	3.3%
3	back	62	63	1.2%
	back	68	71	4.0%
	sitting	65	68	4.7%
4	back	83	79	4.9%
	back	80	74	7.9%
	sitting	100	90	10%
5	back	70	67	4.2%
	back	77	74	3.4%
	sitting	86	75	13.2%

In Table 3.4 are the results shown of the heart rate measurements. The values were calculated by using the Fourier transform on the measurements of the heart rate transmitter and afterwards using the first non-zero peak of the frequency spectrum to determine the heart rate, as seen in Figure 3.14. The accuracy of this part of the design is 95.2% as the average difference between the external source and the measurements was 4.8%. Because the deviance of the blood pressure monitor was 5% the actual accuracy of the test design would be different. This results in an accuracy between 91% and 99% and thus the design requirement for the heart rate is met. Because the heart rate monitor is an integrated band around the chest it is posture and position independent. Like the respiratory rate the algorithm group also failed to implement this function. With this it is impossible to determine if the test design is a valid system with which the algorithm can be verified.

3.3.4. Physical Design

The last requirement that was looked at was the physical design requirement. The first part of this requirement was that the design had to be wireless so that the wearable does not interfere with the patient wearing it. This was met because the integrated wireless module (WiFi) of the raspberry was used in order to send the data to the computer. On the wearable was also a battery attached and thus no power cable had to be attached. The next parts that were looked at were the re-usability, 5 minute setup and non-invasiveness of the design. This design is based on a heart rate monitor that is mainly used in sports and fitness sector and thus the re-usability is guaranteed as no one would buy a device that can only be used once in this sector. The heart rate monitor used in this prototype had an internal battery life of 2500 hours, but because of the casing a new one has to be acquired. The setup time in the prototype was less than five minutes because of its easy to open and close clasp on the side and the position on the body required for the electrodes are fast to be located. As for the non-invasiveness this design does not require anything to be stuck to the body, like the stickers used in hospitals ECG's. The next part of the requirement that was looked at was the was the influence of the design on the sensors under the mattress. This requirement wasn't met as seen in Table 3.2. In this Table it can be seen that sensor 3 has a higher value with the wearable than without. In the end the total cost of the prototype was 201.50 euros and this was within the budget of 500 euros. Therefore this part of the requirement was also met. For the links to the websites where the components were purchased see appendix A.

3.4. Assessment

The current design has met both the primary and secondary design requirements that were set, while part of the tertiary were not met. The current design is able to measure patient posture, respiratory rate and heart rate above the required accuracy. It is possible to measure heart rate independently of patient posture, since the posture of the patient does not influence the location of the heart sensor electrodes on the patient's body. It is also theoretically possible to measure respiratory rate independent of patient posture, however further testing in this aspect is required. The product is completely wireless and it is possible to setup within 5 minutes. The design however does influence the sensor data of the sensor group when the test subject was on his stomach, so this requirement wasn't met in this case. The design was comfortable enough to wear for at least an hour of testing and the design was within budget.

The current design could be considered to be successful because it is able to determine the different bed posture that were used by the algorithm with a high degree of accuracy. The advantages of the current design was its high accuracy in all its functions and that its completely wireless and easy to setup. The disadvantages are that the system influences the sensor pad and that because the system is wireless it has a battery life which can be a problem when longer use is required.

3.5. Next Steps

In the future the first thing that has to be looked at is the size of the components that are currently in use. In particular the battery and the raspberry pi are the biggest component that are in use. The raspberry pi 3 B can be replaced with the raspberry pi zero as this micro controller is smaller. This micro-controller however was not used in the current prototype as this was not yet supported in the raspberry pi Matlab hardware package. Another option is to implement a completely different micro controller to replace the raspberry pi. The other component that can be looked at would be the battery, however decreasing the size could result in decreased battery life. The second thing that can be improved upon is the sampling frequency of the raspberry pi. This can be done in two different ways. The first is to not use the Matlab hardware package but create a python script to handle the communication between the raspberry and the computer. The second method would be to use a micro controller like the one used by the sensor group as they achieved a sampling frequency of 67 Hz. Their current prototype however isn't wireless yet. With a higher sampling frequency it becomes easier to detect the respiratory rate and if the sampling frequency can be increased enough the heart rate receiver can be attached to the prototype making the entire testing system a single entity.

A

Prototype

Raspberry Pi

Raspberry pi 3 model B V1.2. This micro controller is a self contained Linux computer. In the prototype it was running the Rasbian wheezy Linux distribution as this was the only distribution Matlab worked with.
With the following link the official site of the raspberry pi can be found: "*https://www.raspberrypi.org/products/raspberry-pi-3-model-b/*".
On the following site was the raspberry pi that was used purchased: "*https://www.bol.com/nl/p/raspberry-pi-3-starter-kit-wifi-noobs-software-tool/9200000056864739/?suggestionType=suggestedsearch*".

ECG Chest Strap

Polar 34T ECG chest strap was used in our prototype as this is one of the few devices of which the receiver is also commercially available.
With the following link the official site of polar can be found: "*https://www.polar.com/*".
On the following site was the polar 34T purchased: "*https://www.adafruit.com/product/1077*".

IMU

6DOF MPU6050 3 Axis Gyro With Accelerometer Sensor Module, was the IMU used in the prototype.
The datasheet can be found at: "*https://www.invensense.com/wp-content/uploads/2015/02/MPU-6000-Datasheet1.pdf*".
On the following site was the MPU6050 purchased: "*https://www.banggood.com/6DOF-MPU-6050-3-Axis-Gyro-With-Accelerometer-Sensor-Module-For-Arduino-p-80862.html*".

Webcam

Knewmart 720p HD wifi night vision baby monitor was used as the webcam within our tests.
On the following site was the webcam purchased: "*https://www.amazon.de/Sicherheit-Innen-IP-Kamera-Wireless-Nachtsicht-KNEWMART/dp/B01MG0AGQO/ref=sr_1_8?ie=UTF8&qid=1494919242&sr=8-8&keywords=webcam+nachtsicht*".

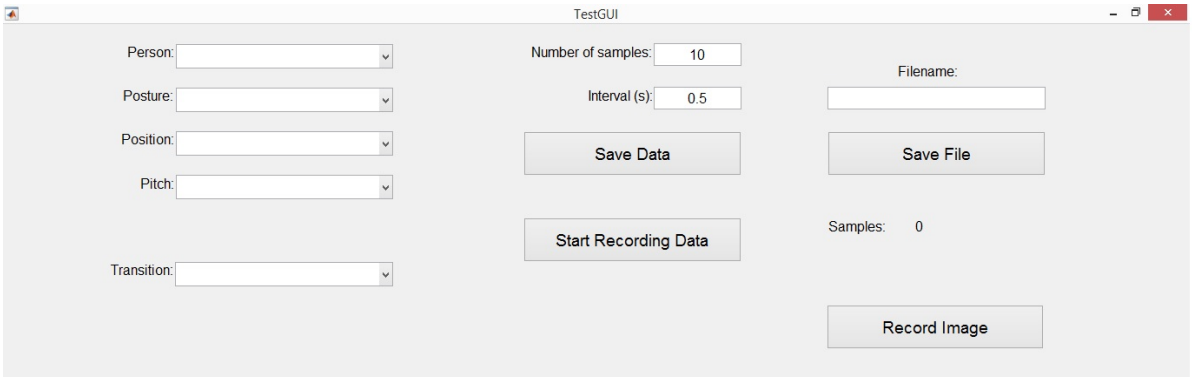
B

Test GUI

The complete code can be found at:"$https://drive.google.com/open?id=0B-NhyH318vjgbTc2SlEydHM2UkU$".

TestGUI.fig

The Graphical User interface that was used during the tests.



TestGUI.m

Below is the section of code visible that takes the data from both the raspberry pi and CSV file created by the micro controller and saves the data in a new file. This is done in order synchronize the data generated by the raspberry pi and the data generated by the micro controller.

```
for i = 1:numberOfSamples

    [x, y, z] = readAcceleration(mpu);
    r = (180*(atan2(y, z)))/ pi;
    p = (180*(atan2(x, sqrt(z^2 + y^2))))/ pi;

    tempData = csvread(filePath);
    delete(filePath);
    [row, ~] = size(tempData);

    r1 = tempData(row, 2);
    r2 = tempData(row, 3);
    r3 = tempData(row, 4);
    r4 = tempData(row, 5);
    r5 = tempData(row, 6);
```

```
    e1 = tempData(row, 7);
    e2 = tempData(row, 8);
    e3 = tempData(row, 9);

    hr = tempData(row, 10);

    mod = [person, posture, position, angle, mP, misc, trans];

    newData = cat(2, [sampleNumber, r1, r2, r3, r4, r5, e1, e2, e3, hr, x, y, z, p, r], mod);

    data = cat(1, data, newData);

    set(handles.text13, 'string', num2str(sampleNumber));
    sampleNumber = sampleNumber + 1;
    pause(interval);
end
```

getserial.py

The code necessary to import the data from the micro controller and save it in a csv file on the computer.

```
import csv
import sys
import serial
import time
filename = 'Resistive_Output.csv'
port = 'COM5'
baud = 921600
lpc1768 = serial.Serial(port, baud, timeout=0.0149)
i = 0

data = []
data.append([])
data.append([])


while True:
        serialstring = lpc1768.readline() # read all characters in buffer
        serialstring = serialstring.decode('utf-8')
        print (serialstring)
        splitstring = serialstring.split(',')

        for _ in range(10):
                try:
                        data[i].append(splitstring.pop(0).strip())
                except Exception:
                        #data[i] = [0,0,0,0,0,0,0,0,0,0]
                        continue

        try:
                with open(filename, 'a', encoding='utf-8', newline='') as csvfile:
                        output = csv.writer(csvfile, lineterminator='\n')
                        output.writerows(data)
                        i=0
                        data = []
                        data.append([])
                        data.append([])
```

C

Measurements

The measurements can be found at: "$https://drive.google.com/open?id=0B-NhyH318vjgdFFLMUk3NzJkTEE$". Below is a fragment of the measurements and in table C.1 are the explanations for every column. In C.2 the numbers of the control signals will be explained and in C.3 will be explained which part of the test data corresponds with which test.

35,1825,2344,5590,3805,9179,3993,4687,4150,0,0.095215,−0.99048,−0.029053,5.4886,−91.68,5,4,2,2,1,1,1
36,1838,2362,5609,3767,9195,3905,4680,4210,0,0.10474,−1.0007,−0.015869,5.9741,−90.908,5,4,2,2,1,1,1
37,1847,2375,5609,3799,9163,4009,4678,4031,0,0.10571,−0.99414,−0.0058594,6.0697,−90.338,5,4,2,2,1,1,1
38,1853,2390,5587,3786,9203,3933,4675,4110,0,0.11865,−1.0042,−0.021729,6.7374,−91.24,5,4,2,2,1,1,1
39,1849,2343,5548,3831,9187,3908,4683,4121,0,0.10205,−0.99902,−0.013184,5.8321,−90.756,5,4,2,2,1,1,1
40,1846,2378,5608,3806,9244,3908,4680,4040,0,0.10278,−0.98999,−0.015381,5.9266,−90.89,5,4,2,2,1,1,1
41,2990,3234,6225,3814,10134,4015,4679,3988,0,0.045166,−0.25049,0.96167,2.6023,−14.6,5,2,2,2,1,1,1
42,3046,3219,6266,3839,10063,3986,4686,4020,0,0.06665,−0.2644,0.98169,3.7508,−15.074,5,2,2,2,1,1,1
43,3044,3218,6195,3871,10164,4032,4677,4077,0,0.05542,−0.26489,0.94629,3.2279,−15.638,5,2,2,2,1,1,1
44,3079,3224,6319,3866,10089,3951,4687,4079,0,0.042969,−0.25146,0.96973,2.456,−14.537,5,2,2,2,1,1,1
45,3042,3220,6404,3824,10165,3983,4674,4059,0,0.056885,−0.27075,0.96118,3.2603,−15.732,5,2,2,2,1,1,1
46,3048,3182,6409,3861,10136,4038,4683,4010,0,0.064941,−0.27637,0.96411,3.7048,−15.995,5,2,2,2,1,1,1
47,3088,3200,6466,3872,10154,4038,4676,3997,0,0.057129,−0.27417,0.96606,3.256,−15.844,5,2,2,2,1,1,1
48,3074,3162,6460,3876,10126,4027,4683,4013,0,0.061768,−0.25781,0.95898,3.5593,−15.048,5,2,2,2,1,1,1
49,3055,3164,6425,3865,10116,3970,4687,4079,0,0.069092,−0.27515,0.9729,3.9093,−15.791,5,2,2,2,1,1,1
50,3011,3183,6416,3885,10128,4017,4680,4030,0,0.082764,−0.26563,0.96582,4.7233,−15.378,5,2,2,2,1,1,1
51,3111,7950,8825,2390,6874,3852,4677,4079,0,0.13159,0.97217,0.27368,7.4235,74.277,5,3,2,2,1,1,1
52,3094,7913,9071,2419,6960,4044,4678,4016,0,0.13989,0.94629,0.29004,8.0451,72.96,5,3,2,2,1,1,1
53,3147,8080,9123,2431,7010,3869,4674,4107,0,0.14673,0.92749,0.3064,8.5428,71.719,5,3,2,2,1,1,1
54,3145,8142,9100,2427,6987,3890,4678,3983,0,0.17529,0.94385,0.27124,10.121,73.967,5,3,2,2,1,1,1
55,3129,8628,9116,2437,7006,4014,4690,4061,0,0.1665,0.97266,0.33081,9.2057,71.216,5,3,2,2,1,1,1
56,3141,8442,9011,2410,7057,3962,4690,4015,0,0.16626,0.93506,0.3313,9.5142,70.49,5,3,2,2,1,1,1
57,3131,8391,8996,2453,7055,4000,4686,4038,0,0.14868,0.93677,0.30737,8.576,71.834,5,3,2,2,1,1,1
58,3150,8513,9097,2452,7054,3963,4688,4033,0,0.16187,0.93774,0.33545,9.2313,70.317,5,3,2,2,1,1,1
59,3143,8498,9090,2430,6987,3885,4680,4087,0,0.15063,0.94556,0.28955,8.6611,72.974,5,3,2,2,1,1,1
60,3170,8484,9395,2460,7051,3977,4689,4122,0,0.16772,0.93286,0.34717,9.5648,69.587,5,3,2,2,1,1,1
61,4623,7543,5678,2087,7415,3752,4677,4282,0,0.17358,−0.15698,−1.0488,9.2957,−171.49,5,5,2,2,1,1,1
62,4789,4304,5337,2198,7738,2416,4678,3147,0,0.068604,−0.24023,−1.0061,3.7945,−166.57,5,5,2,2,1,1,1
63,4850,8522,6133,2033,6165,3653,4681,3145,0,0.11157,−0.074219,−1.071,5.933,−176.04,5,5,2,2,1,1,1
64,4789,7514,6345,2010,6653,4227,4687,4028,0,0.10205,−0.028564,−1.019,5.7165,−178.39,5,5,2,2,1,1,1
65,4786,7188,6298,1976,6624,3917,4693,3968,0,0.097656,−0.017822,−1.0352,5.3885,−179.01,5,5,2,2,1,1,1
66,4782,7088,6163,1972,6692,3997,4667,4095,0,0.099854,−0.014648,−1.0278,5.5483,−179.18,5,5,2,2,1,1,1
67,4870,7752,6321,2105,6867,3860,4682,4108,0,0.12622,−0.066895,−1.0244,7.0094,−176.26,5,5,2,2,1,1,1
68,4830,7436,6132,1933,6854,3825,4675,4021,0,0.12134,−0.049561,−1.0276,6.7266,−177.24,5,5,2,2,1,1,1
69,4837,7172,6084,1951,6921,3896,4683,4058,0,0.10254,−0.061523,−1.0183,5.7396,−176.54,5,5,2,2,1,1,1
70,4846,7771,6118,1959,6800,3564,4682,4048,0,0.12646,−0.051514,−1.0371,6.9438,−177.16,5,5,2,2,1,1,1

Table C.1: The meaning behind every column within the test files

Column number	Explanation
1	Sample number, starts at 1 each first data measurements
2	Piezo-resistive sensor 1 value
3	Piezo-resistive sensor 2 value
4	Piezo-resistive sensor 3 value
5	Piezo-resistive sensor 4 value
6	Piezo-resistive sensor 5 value
7	Piezo-electric sensor 1 value
8	Piezo-electric sensor 2 value
9	Piezo-electric sensor 3 value
10	Heart rate receiver
11	Accelerometer x value
12	Accelerometer y value
13	Accelerometer z value
14	Patient pitch
15	Patient roll
16	Person on the bed
17	Posture
18	Position
19	Pitch
20	Multiple persons
21	Misc
22	Transitions

Table C.2: The meaning behind behind the numbers within the control signal columns

Number	Person	Posture	Position	Pitch	Multiple persons	Miscellaneous	Transitions
1	No one	-	-	-	Not used	-	Not used
2	Andy	Back	Middle	0°			
3	Bas	Left	Left	30°			
4	Danny	Right	Right	45°			
5	Douwe	Stomach				Influence Stomach	
6	Thomas	Left 30°					
7	Wim	Right 30°					

Table C.3: The divisions of the data files, given are the sample numbers and the results of the external sources.

Filenam	Static	HR-B1	HR-B2	HR-S	RR	Dynamic
Testfile11.txt	1	561, 82	4966, 75	9109, 80	-	-
Testfile12.txt	-	-	-	-	862, 9	5487
Testfile21.txt	1	-	-	-	-	-
Testfile22.txt	1	5134, 72	8050, 66	10918, 69	13455, 15	18099
Testfile3.txt	1	541, 62	3935, 68	7117, 65	12905, 15.5	16476
Testfile4.txt	1	1149, 83	5322, 80	8756, 100	13848, 7.4	17205
Testfile5.txt	1	541, 70	4558, 77	7691, 86	11083, 12.5	16557

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