NTNU – Trondheim
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Vibrations' Influence on Human Physiology

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Abstract

Vibrations of one type or another are present almost every minute of our daily lives. Much research has been done on high-frequency vibrations' influence on human physiology, though less is known about the impact of low-frequency vibrations.

This thesis investigates low frequency, whole-body vibrations influence on human physiology. We've attempted to determine if there is a correlation between resting heart rate and vibration magnitude in 40 adult test-subjects exposed to intervals of differing vibration magnitude.

40 students (age 19 to 34) were subjected to five consecutive 4-minute intervals of differing whole-body vibrations, with constant amplitude of 5 cm.

A significant ($p < 0.02$) reduction in mean heart rate was found between interval 3 (0.52 Hz) and interval 4 (0.28 Hz). No other significant changes between consecutive intervals were found, though a general decrease in heart rate over time was observed. These results could indicate that a reduction in vibration magnitude has a relaxing effect on the human body, though further studies are needed to verify this.

The results of this thesis suggest that heart rate alone does not provide sufficient information about vibrations effect on human physiology. Future studies should consider additional physiological factors to monitor when conducting this type of experiment.

IV

Norsk sammendrag

Vi utsettes for vibrasjoner av ulike typer i nesten alle situasjoner i livet. Mange studier har blitt gjort på høyfrekvente vibrasjoner påvirkning på mennesker, men lavfrekvente vibrasjoners påvirkning er ikke like godt kjent.

I denne masteroppgaven vil vi studere lavfrekvente full-kropp-vibrasjoners påvirkning på menneskers fysiologi. Vi undersøker om det er en sammenheng mellom hvilepuls og vibrasjons-styrke i 40 voksne testpersoner utsatt for vibrasjonsintervaller av forskjellig intensitet.

40 studenter (alder 19 til 34 år) ble utsatt for 5 etterfølgende 4 minutters intervaller med sinusformede full-kroppsvibrasjoner. Vibrasjonene i hvert intervall hadde ulike frekvenser og konstant amplitude 5 cm.

En signifikant ($p < 0.02$) forskjell i gjennomsnittlig puls ble funnet mellom intervall 3 (0.52 Hz) og intervall 4 (0.29 Hz). Ingen andre signifikante endringer mellom etterfølgende intervaller ble funnet men en generell nedgang i puls over tid ble registrert. Dette kan bety at en nedgang i vibrasjons-styrke har en avslappende effekt på kroppen, men videre studier er nødvendig for å verifisere dette.

Resultatene i denne oppgaven tilsier at puls alene ikke gir et tilstrekkelig bilde over ulike vibrasjoners påvirkning på mennesker fysiologi. Senere studier bør vurdere andre fysiologiske faktorer som mål på vibrasjoners innflytelse på mennesker.

Acknowledgements

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Foremost, I would like to thank my supervisor, Professor Martin Steinert, and co-supervisor, Professor Terje Rølvåg, for helping me through this thesis.

Thanks also to Andre Steinert and Gabriela Dahle at the department office for making everything easier, to Halvard Støver for all your help and to Professor Bo Henry Lindqvist and Thomas Øvestad for invaluable help with statistics calculations. A special thanks to Børge, Per-Erik and Alex in the workshop for your help and (almost) endless patience, and to the guys in the office for many good times!

Lastly, I would like to thank my friends and family for all your support and my girlfriend, Ingrid, for your boundless patience and for keeping me alive these last few months!

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List of Symbols and Abbreviations

Δ	Difference (Delta)
Δ_{ij}^{n}	Difference in mean heart rate between interval i and j, for subject n.
μ	Population mean
σ	Standard deviation
φ	Angle [rad]
ω	Angular frequency [1/s]
x	Data point from sample [BPM]
$\bar{x}$	Sample mean
$\tilde{x}$	Sample median
$\bar{x}_i^n$	Mean heart rate in interval i for subject n [BPM]
$\bar{x}_{i,norm}^n$	Mean heart rate, normalized around 0
A	Amplitude
ANOVA	Analysis of variance
BPM	(heart-) Beats per minute
F	Force [N]
f	Frequency [Hz]
g	Gravitational constant 9.81 m/s^2
i and j	Interval number
n	Subject number
rms	Root-mean-square
t	Time [s]
ϕ_i	Mean of normalised mean values of interval i

1 Introduction

With this project we seek to gain a better understanding of the influence of low frequency vibrations on the human body. The thesis is written as a collaboration between NTNU and the company Colicot AS, who has developed a cradle for infants with colic. The Colicot cradle (Figure 1-1) utilizes a low-frequency harmonic motion that is supposed to relieve pain and calm colicky infants. Some research has been done on the effect of harmonic vibration in calming children (Brackbill 1973, Pederson 1975), and we initially wanted to evaluate Colicots effect on infants with colic. However, it proved challenging to recruit test subjects of the appropriate group (infants between 4 weeks and 4 months, (Eri and Mevåg 2014)) and strict rules from the Regional Ethical Committee, REK, made it difficult to gather meaningful data. Our initial tests of the cradles soothing effect on infants were therefore inconclusive. We decided to refocus the thesis and investigate physiological effects in adults exposed to low-frequency harmonic vibrations. The type of vibrations studied are based on those utilized by the Colicot cradle.

Figure 1-1 The Colicot cradle

Vibrations influence on human physiology is a wide and complex field that involves a wide range of disciplines. Most research on the subject is focused on high-frequency vibrations (in the range of 10 Hz to 80 Hz and above), with small amplitudes (in the millimetre or micrometre scale). These types of vibrations are present in many common environments such

as in tall buildings, near heavy traffic, close to operating machinery etc. and may still have unknown long term effects. (Paschold 2008)

Less research has been done on low-frequency vibration's effect on the human body (f up to around 2 Hz). A study by Endo, Kimura et al. (2010) on vibrations and sleepiness on trains indicate that a frequency below 2 Hz (and especially in the area of 1 Hz) aid humans in falling asleep. Brackbill (1990) and Pederson (1975) have studied the effects of low frequency rocking of children and Griffin (1990) summarizes some research on frequencies that induce motion sickness (f below about 0.5 Hz).

We encounter vibrations of one form or another practically every second of our lives and increased understanding and knowledge of low-frequency vibration's effect on the human body can therefore be useful in many areas of society. It may improve our understanding or treatment of insomnia or other sleep related disorders and may help the development of devices or treatments to increase general sleep quality. Knowledge about especially soporific or enervating frequencies is also of interest to manufacturing companies. For instance, train companies might improve the quality of their ride by having the train vibrate at especially soporific frequencies. Car manufacturers, however, would want to stay well away from sleep-inducing frequencies and perhaps focus on frequencies that keep the driver alert. An understanding of why some frequencies induce motion sickness can also be useful to these companies, among others. Knowledge about vibration's calming effect on infants (especially infants with colic or other sleep related diagnoses) can aid in relieving pain and stress, and help infants sleep. Indirectly, this may relieve stress and improve sleep in parents.

In this thesis we investigate a physiological reaction in adult humans subjected to whole-body harmonic vibrations. By monitoring heart rate of resting subjects exposed to consecutive intervals of vibrations with amplitude of 5 cm and frequencies 0.29 Hz and 0.52 Hz we look for correlations between resting heart rate and vibration magnitude. Our experiment set-up and vibration properties were chosen based on the aims of our study, literature reviews and pilot tests.

2 Aims

With this thesis we hope to aid future studies and development of the Colicot cradle. To gain a better understanding of how vibrations affect humans we seek to answer the following question:

- Does vibration magnitude influence heart rate in adult humans?

2.1 Hypotheses

A hypothesis to be investigated was proposed based on the aims:

H0: No change in heart rate can be observed when adult humans are subjected to intervals of sinusoidal, whole-body, head-to-toe vibrations with amplitude 5 cm and frequency 0.28 Hz and 0.52 Hz, respectively.

The alternative hypothesis:

H1: A significant difference in heart rate is observed between consecutive vibration intervals.

3   Theory

3.1   What are vibrations?

Vibrations are oscillatory motions around an equilibrium point (Chen 2014). They can take an almost infinite number of forms, from the simple harmonic motion of a mass-spring system, through shocks and transient responses, to the non-stationary, random vibrations encountered when driving on a bumpy road. We can define and categorize vibrations by a great number of factors. Among the more common are frequency, amplitude, acceleration, and duration. (Griffin 1990) 41

3.2   Vibrations magnitude

Finding a good standard measurement of vibration magnitude, or severity, is no easy task. With rising frequency, different vibration-properties will have the most pronounced effect on the surroundings. In addition to frequency; displacement, velocity, acceleration magnitude and jerk can all influence the effect of vibrations and are common measures of vibration magnitude. Duration of exposure and dose-effect relationships serve to complicate matters even further. (Griffin 1990) 7

In our experiment (Chapter 4) we will use a crank mechanism to induce vibrations (Figure 4-3). The equations of motion and forces induced by this mechanism are shown in Table 3-1.[1] As can be seen by Equation 3-1 through Equation 3-5, force, frequency and acceleration have a non-linear relationship. Small changes can therefore produce large effects. In addition, vibrations with frequencies close to object's resonance frequencies can have unpredictable and sometimes disastrous effects, the Tahoma Narrows bridge collapse in 1940 is a well-known example.

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[1] The equations accurately describe the motions transferred to the mattress in our experiment (Chapter 4) because the Connector arm (l) (Figure 4-2) is much longer than the amplitude (A); A << l.

Table 3-1 Equations of motion and force for the crank mechanism used in this thesis

Displacement	$x \approx A\cos(\omega t)$	*Equation 3-1*
Velocity	$v_x \approx -\omega A\sin(\omega t)$	*Equation 3-2*
Acceleration	$a_x \approx -\omega^2 A\cos(\omega t)$	*Equation 3-3*
Jerk	$j_x \approx \omega^3 A\sin(\omega t)$	*Equation 3-4*
Force	$F = ma_x \approx -m\omega^2 A\cos(\omega t)$	*Equation 3-5*

3.3   Human perception of vibrations

Human perception of vibration varies with the properties mentioned above (Parks and Snyder 1961). The exponential relationship between force, frequency, amplitude and acceleration seen in Equation 3-5 means that even small changes in any one of these factors can greatly alter our perception of the vibrations.

During pilot tests (Chapter 3.5 and Appendix C6 Pilot tests) in the early stages of this study subjects experienced that small changes to either vibration frequency or amplitude can produce a very different feel. Vibrations at 0.2 Hz with 5 cm amplitude were barely felt, while changing the frequency to 0.7 Hz resulted in a very uncomfortable experience. Increasing the amplitude to 10 cm while keeping frequency at 0.7 Hz threatened to tear the test equipment apart!

Perception can vary greatly with the type of vibration (shock, sinusoidal, non-stationary random etc.), with the duration of exposure (Griffin 1990), and with different dose-effect relationships (Griffin, Bovenzi et al. 2003). Perception further depends on which parts of the body are subjected to the vibrations. Griffin (1990) separates between whole-body vibrations and local vibrations, where whole body vibrations are relevant for this thesis. Whole-body vibration is the case of the entire body being exposed to the vibrations (Paschold 2008). This occurs typically when the *"body is supported on a surface that is vibrating"* (Griffin 1990) 27.

Much like bridges, humans too can be vulnerable to resonance. Frequencies in otherwise harmless ranges can cause severe effects (Wasserman, Wilder et al. 1997).

> *The human body as a whole and its individual organs have differing natural frequencies. If the transmitted external vibration frequency approaches or equals the natural frequency, resonance will occur. The entire body or affected body organ can vibrate at an amplified magnitude that is greater than the external source vibration entering the body (...)* (Paschold 2008)

For head-to-toe vibrations, Wasserman, Wilder et al. (1997) suggest that frequencies in the range of 4 to 8 Hz cause the most severe resonance problems in humans. The frequencies studied in this thesis are approximately an order of magnitude below this range.

3.4   Physiological response to vibrations

> *Physiological responses to vibrations may be considered as changes in normal physiological rhythms induced by vibrations, as opposed to disease or changes associated with disease caused by vibrations.* (Griffin 1990) 173

As vibrations can affect practically every part of our bodies there is an endless list of physiological factors one could study. The cardiovascular-, respiratory- and central nervous systems, motor processes, endocrine and metabolic responses and the sensory system have all been reported to experience some change when a person is subjected to vibrations of different frequencies. (Griffin 1990)

In this thesis we will study change in heart rate as the physiological parameter. Heart rate was chosen because it is a well-known physiological parameter, it is relatively easy to measure and changes in heart rate due to vibrations have been reported (Rylands and Cole 1985).

3.5   Our experiment

Pilot tests were performed with our experiment apparatus (Chapter 4.1.2). A subject was exposed to a range of different vibration magnitudes to provide information on which frequencies and amplitudes were suited to our experiment and equipment. Specific amplitude and frequencies to study were chosen based on our aims and the results of the pilot tests (Appendix C6 Pilot tests).

In this thesis we will study the effects of vibrations with the properties listed in Table 3-2. An explanation of the different properties and why they were chosen follows.

Table 3-2 Properties of the vibrations studied in this thesis

Property	Value
Waveform	Sinusoidal
	Pendulum, single pivot point
Frequencies	0.29 Hz
	0.52 Hz
Amplitude	5 cm, constant
Measure of magnitude	Frequency
	RMS acceleration
Mode	Forced oscillation
Interaction with body	Whole-body vibrations
Direction of movement	Head-to-toe
Duration of experiment	20 min
Duration at each frequency	4 min

3.5.1 Sinusoidal vibrations

Sinusoidal vibrations were chosen for our experiment because we want to study the effect of a single frequency of motion at a time. This is possible only when the vibration is sinusoidal. (Griffin 1990)

3.5.2 Measure of magnitude

Frequency was chosen in this thesis because it is an intuitive measure of vibration magnitude. It is often easy to measure (and in our case control) and is commonly used to classify

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vibrations across many fields of study (Griffin 1990). Griffin (1990) 8 also states that *"human response can be highly dependent on the frequency of vibration"*

Griffin (1990) further suggests that acceleration is the most important factor for vibration effect for frequencies below 1 Hz. Pederson (1975) states that rocking frequency and acceleration has a direct relationship to its effectiveness in calming infants. Acceleration is also easy to measure and was chosen as an additional indication of vibration magnitude.

3.5.3 Frequencies

A frequency range from approximately 0.2 to 1.2 Hz was chosen based on the aims of the study, results of the pilot tests (Appendix C6 Pilot tests) and literature findings. Pederson (1975) found that frequencies of 0.75 and 1 Hz had a soothing effect on infants and Endo, Kimura et al. (2010) suggests that frequencies below 2 Hz aids adult humans in falling asleep. Frequencies around 1 Hz proved to be especially soporific in their study. The Colicot cradle also utilizes frequencies around 1 Hz. The specific frequencies of 0.29 and 0.52 Hz were chosen based on the findings in the pilot study. The effects of frequencies below 0.29 Hz were unnoticeable and for frequencies above 0.52 Hz the movement was perceived as jerky.

3.5.4 Amplitude

The amplitude was chosen to be constant at 5 cm based on the results of the pilot tests. Constant amplitude (contra constant acceleration) ensures that increasing the frequency also increases acceleration (by the power of 2, Equation 3-3). Thereby, we maximize the change in forces on the body and vibration magnitude with each frequency change. The specific amplitude of 5 cm was chosen based on the results of the pilot tests.

3.5.5 Acceleration

Given vibration frequency (f) and amplitude (A) the resulting theoretical acceleration can be calculated. The root-mean-square (rms) value of accelerations will be used in this thesis, as recommended by Griffin (1990).

Table 3-4 shows the theoretical acceleration and rms-acceleration studied in this thesis, calculated with Equation 3-3 and the equations listed in Table 3-3 below.

Table 3-3 Calculation of theoretical acceleration and root-mean-square acceleration

Angular frequency [1/s]	$\omega = 2\pi * f$	*Equation 3-6*
Acceleration in x-direction	$a_x = \omega^2 A\cos(\omega t)$ $= (2\pi f)^2 * A\cos(2\pi f * t)$	*Equation 3-7*
rms-value of sinusoidal acceleration	$a_{x,rms} = \dfrac{a_x}{\sqrt{2}}$	*Equation 3-8*

Table 3-4 Frequencies, amplitude, theoretical acceleration and rms-acceleration studied in this thesis.

Frequency [Hz]	Amplitude [m]	Theoretical acceleration, x-direction $\left[\frac{m}{s^2}\right]$	Theoretical RMS-acceleration $\left[\frac{m}{s^2}\right]$
0.29	0.05	0.161	0.1138
0.52	0.05	0.525	0.3995

3.5.6 Duration

The duration of exposure at each frequency was set to 4 minutes. Jennings, Bberg et al. (1981) suggests that sustained change in heart rate generally last more than 30 seconds. Four minute intervals proved through the pilot tests to be sufficient time for the heart rate of subjects to stabilize after changes and to provide sufficient data at a stable heart rate.

3.5.7 Whole-body vibrations

Whole-body vibrations were chosen because it best adheres to our aims. The Colicot cradle utilizes whole-body vibrations and we seek to study the effect of vibrations on heart rate, not specific effects of vibrations in specific body parts.

3.5.8 Head-to-toe

The literature does not give a clear view of how much the direction of vibrations matter. Pederson (1975) found no significant effect of the direction of vibrations on infants' activity level, while Griffin (1990) states that direction of vibrations can be important. As the Colicot cradle utilizes head-to-toe vibrations this form was chosen for our experiment.

3.5.9   Forced motion

A forced motion (contra a free pendulum) allow us careful control of the vibration frequency, while keeping the amplitude constant.

A test rig utilizing natural frequency was built and tested during the early works on this master thesis. However, given our time frame and resource limits, it turned out to be too complicated to build a test rig where frequency could be changed smoothly.

3.5.10 Mattress pendulum properties

The mattress-pendulum set-up used in our experiment can be seen in Figure 4-1. A mattress is suspended by ropes hung from a ceiling crane, allowing for a pendulum motion. A single pivot point for the pendulum was chosen because it best approaches a perfect pendulum swing, which may make the experiment easier to replicate in future studies.

The natural frequency of a simple pendulum is determined by the rope length (L), as seen by Equation 3-9. Ropes of 4.5 meters were used in our experiment, giving our mattress-pendulum a natural frequency of 0.235 Hz. The rope length was chosen in an attempt to avoid resonance with the forced frequencies used in our experiment.

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{L}}$$

Equation 3-9

3.5.11 Confounding factors

Griffin (1990) describe a long list of factors that should be considered when conducting experimental studies on whole-body vibration and Jennings, Bberg et al. (1981) states that heart rate is sensitive to environmental change. We must therefore seek to carefully control many factors when conducting our experiment.

Among the environmental factors relevant for our study are: room temperature, time of day, light conditions, background noise, sudden loud noises, general activity level in the workshop, airflow from people passing, smells and unwanted movements in the test equipment. Subjective factors include: initial stress level, stimulants (i.e. caffeine and nicotine), gender, age, body mass, physical condition, personality, resting posture / position, expectations and social discomfort.

The experiment was conducted in the workshop at the Department of Engineering Design and Materials, NTNU, and many environmental factors were therefore difficult to control. We

sought to minimize what we thought were the most influential environmental factors: Subjects were offered eye mask and hearing protection to minimize light and noise pollution, and blankets to control temperature. Subjects were given the choice of using these so as not to cause unnecessary social discomfort. Other people in the workshop were kept at a distance to avoid bumping into the mattress and to keep errant airflows and smells from disturbing subjects.

We do not expect initial stress level, stimulants or physical conditions to affect our results. Since we're studying change in heart rate, and not comparing the actual heart rates of subjects, these factors should not influence our results.

4 Method

4.1 Experiment set-up

4.1.1 Subjects

The subjects were 36 volunteering students from the Department of Engineering Design and Materials, NTNU. Four subjects were tested twice, for a total of 40 data sets. Subjects age, sex, height and weight is found in Appendix B Subject data.

4.1.2 Apparatus

The test setup was designed to produce a forced sinusoidal oscillation, as described in Chapter 3.5. A framed mattress was raised above the floor by ropes hung from a ceiling crane as seen in Figure 4-1. A BEVI electric motor provided the force for oscillations. A "belt and pulley" gearing system reduced the speed and increased the force of the electric motor. A stiff aluminium arm connected the framed mattress to the gearing system to produce the forced oscillation. The experiment set-up schematics can be seen in Figure 4-2 and Figure 4-3. Technical data on the apparatus is found in Appendix F Technical data.

Figure 4-1 Experiment set-up. Mattress hanging from ceiling crane
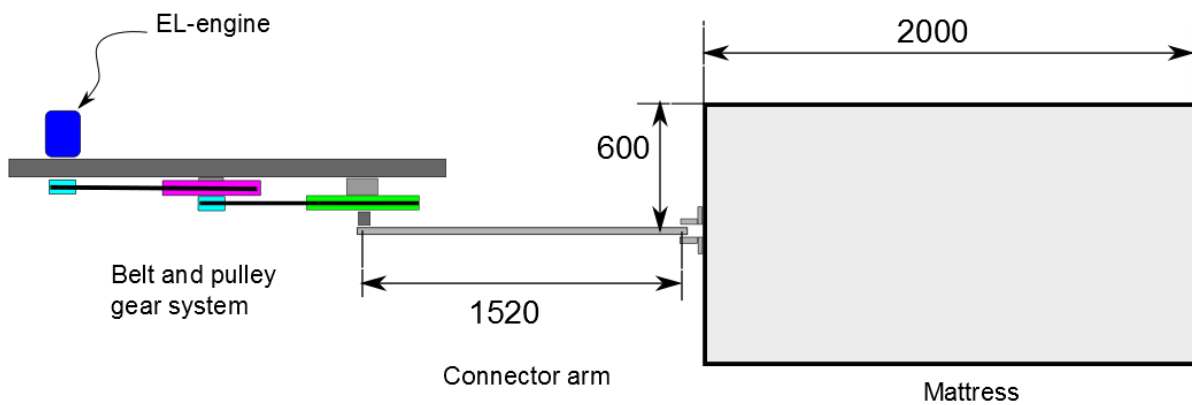
Figure 4-2 Experiment set-up schematics, top view. All measures in millimetres.
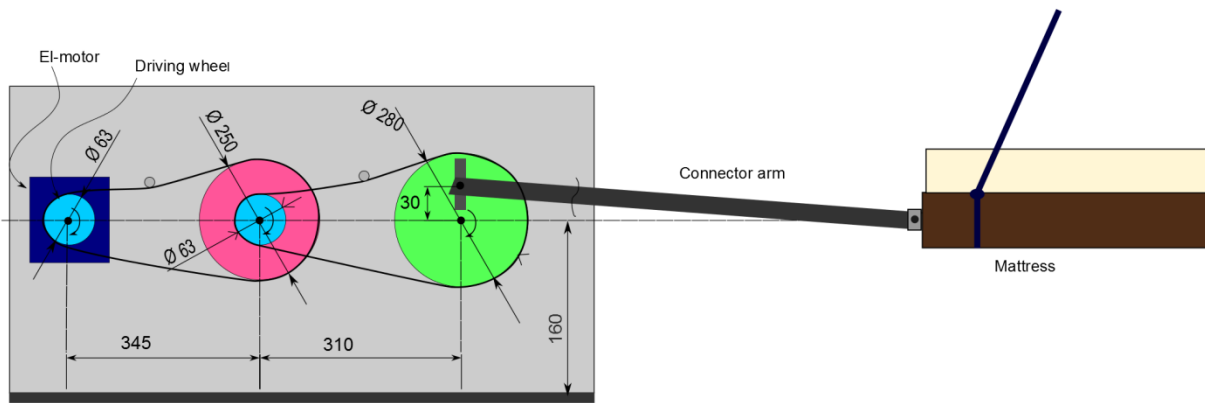
Figure 4-3 Experiment set-up schematics, side view. All measures in millimetres.

The el-motors' speed was regulated by a commutator transformer. The commutator transformer was regulated by hand while the resulting angular frequency was monitored by applying a handheld tachometer to the driven pulley wheel.

4.1.3 Data gathering

The subjects' heart rate was recorded by an Arduino E-health unit with an ECG module. The acceleration of the mattress and test subject was measured by a 3-axial accelerometer on the Arduino unit. Technical data on the Arduino modules are found in Appendix F Technical data.

4.1.3.1 Data and sampling rate

Data was collected at a sampling rate of 72 samples per second. Each data sample contained five columns, logging a timestamp, ECG- and acceleration data. The timestamp was logged as milliseconds from program start. The heart rate data was logged as a rational number between 0.0 and 5.0. The acceleration data consisted of three rational numbers between -2.0 and 2.0, respectively indicating acceleration in direction x, y and z in units of g [9.81 m/s^2]. A basicentric coordinate system was defined for the acceleration directions, relative to the mattress surface, as can be seen in Figure 4-5. Arduino code is found in Appendix D Arduino code.
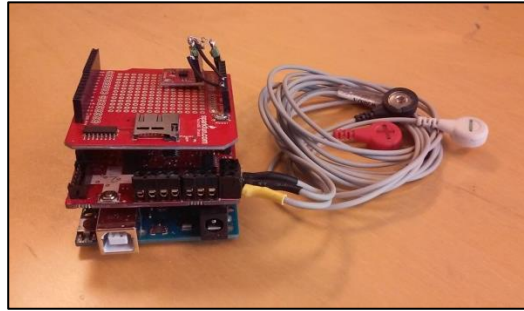
Figure 4-4 Arduino E-health with ECG module and accelerometer
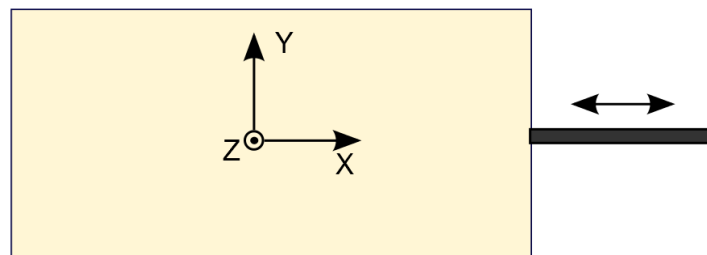
Figure 4-5 Basicentric coordinate system relative to the mattress

4.2 Procedure

3-lead ECG electrodes were placed on subjects' bodies as shown in Figure 4-6. The subjects were given the option of using eye mask and hearing protection for their resting comfort and were then asked to lie down in the middle of the mattress, with feet towards the connector arm (Figure 4-3 and 4–7). The subjects were free to choose their own resting position (on back, side etc.).

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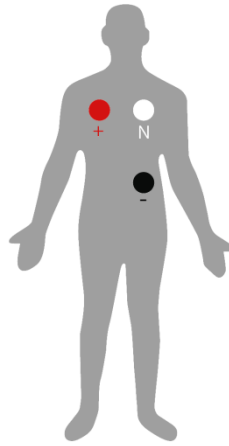
Figure 4-6 ECG electrode placement. Figure shows the placement on the body of the +, - and neutral ECG electrodes.

The subjects were then subjected to five consecutive intervals of 4 minutes, for a total of 20 minute. The intervals with corresponding frequency is found in Table 4-1.

Table 4-1 Interval numbers with corresponding vibration frequency

Interval number	Vibration frequency
Interval 1	0 Hz (no movement)
Interval 2	0.29 Hz
Interval 3	0.52 Hz
Interval 4	0.29 Hz
Interval 5	0 Hz (no movement)

It was attempted to make the transition between intervals as smooth as possible, over a period of approximately 20 seconds, so as not to disturb the subjects. Subjects were not notified when the intervals changed.
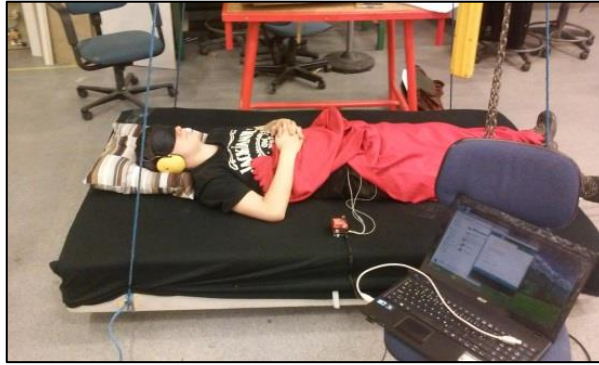
Figure 4-7 Test subject experiencing vibrations

4.3 Data processing

Data from individual test subjects was analysed with MathWorks Matlab 2014b. Analysis code is found in Appendix E Matlab code.

4.3.1 Acceleration

The root-mean-square (rms) value of the acceleration in x- direction was calculated for each vibration interval for all subjects. The average of rms-acceleration value of each interval was then calculated and is shown in Table 5-1. Calculation procedure is found in Appendix E4 Acceleration processing.

4.3.2 ECG

ECG-data was plotted against time, producing the recognisable ECG-signal shown in Figure 4-8.
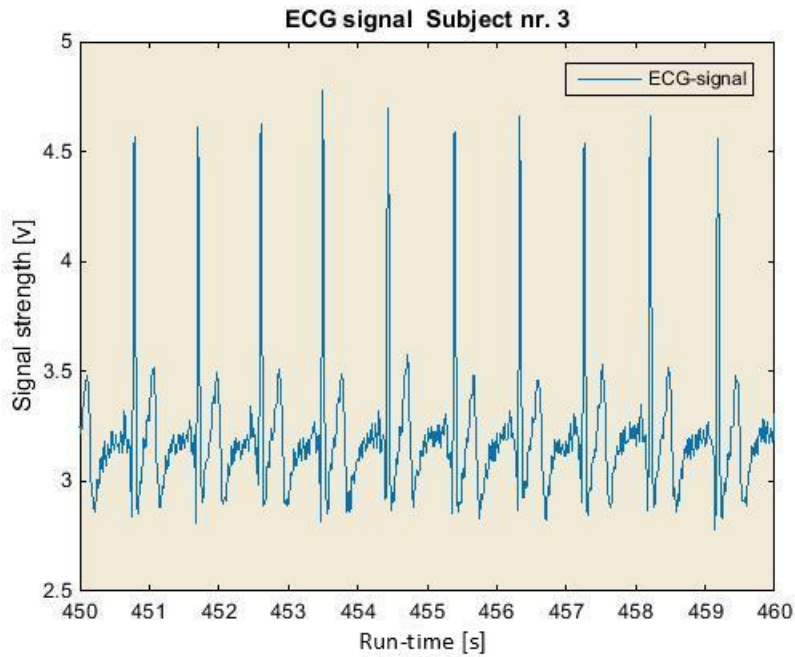
Figure 4-8 ECG-signal example from one subject

Filters were applied to clearly outline each heart-beat. An order 500 window-based finite impulse response filter (Matlab command: fir1), with normalized cut-off frequency $\frac{1}{72*2}$ (0.00694 Hz) was applied to remove low frequency drift. To emphasise the spikes the resulting signal was raised to the power of 2, producing the graph shown in Figure 4-9 when plotted against time.
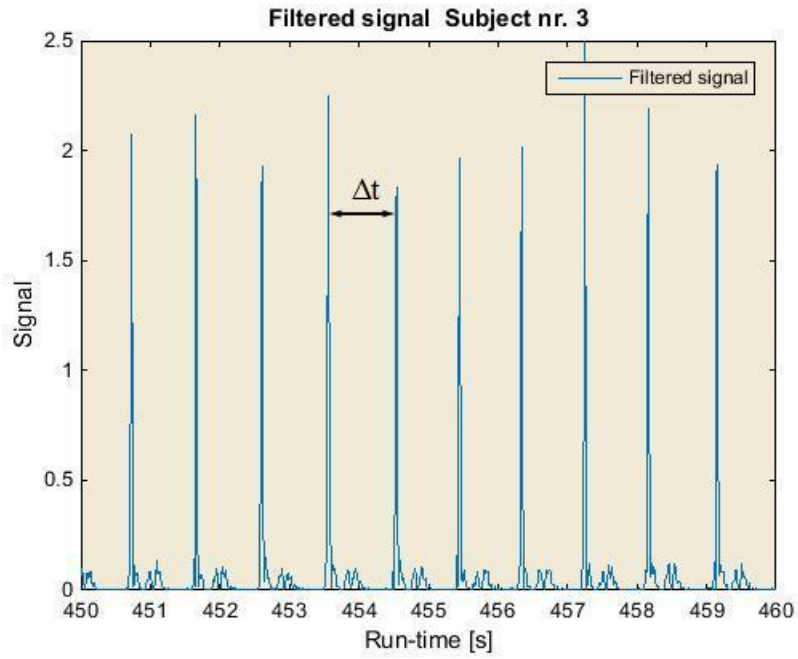
Figure 4-9 Filtered ECG-signal. Individual hear-beats (spikes) can now be clearly detected.

Time between individual heart beats, Δt, was measured and transformed to momentary heart rate, or pulse, in beats per minute by Equation 4-1.

$$\frac{60}{\Delta t}$$ ***Equation 4-1***

Heart rate was then plotted against time, producing the graph in Figure 4-10.

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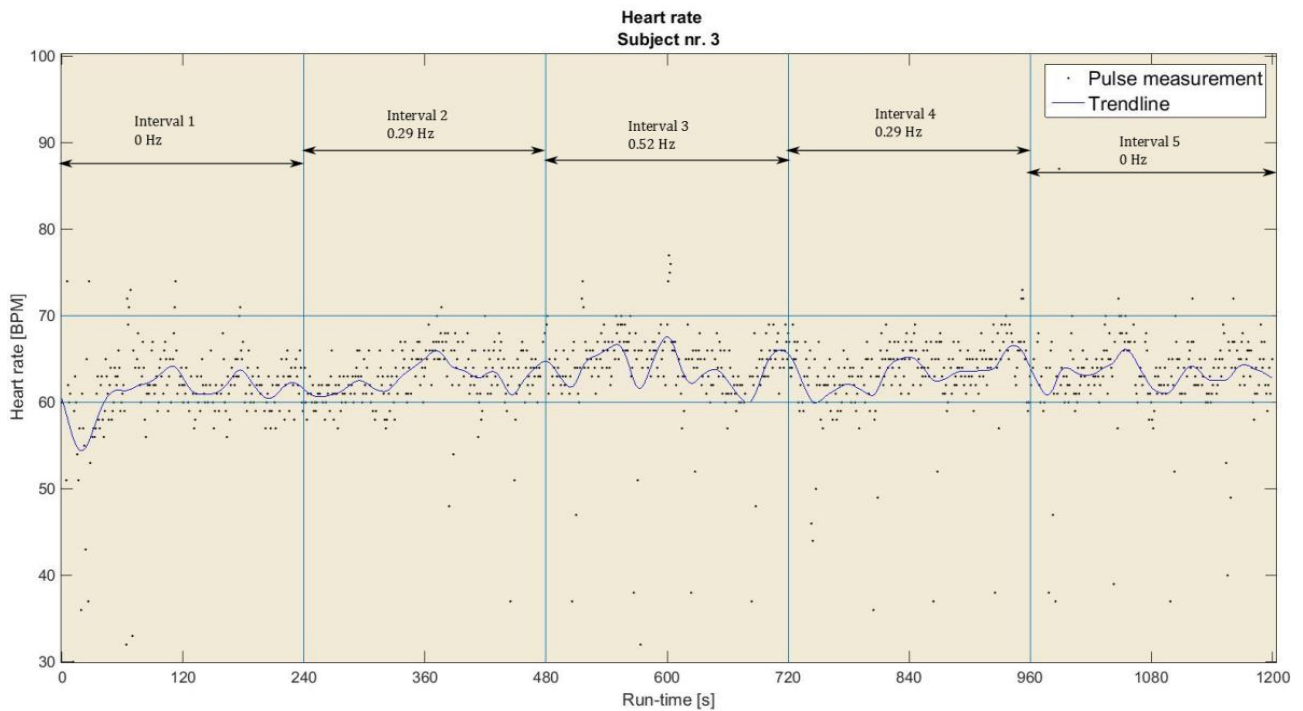
Figure 4-10 Heart rate data for one subject over the entire 20-minute experiment. Individual heart rate measurements are shown as dots. A trend-line is fitted to the data to show the variation in hear rate.
Vertical lines separate 4-minute intervals. Horizontal lines show 60 BPM and 70 BPM thresholds.

Measurement errors can produce extreme values (outliers) in our data. (Jennings, Bberg et al. 1981) Outliers were identified by the following procedure:

The heart rate data-points were separated into intervals of 30 consecutive heart-beats. For each interval the median, $\tilde{x}$, and standard deviation, σ , was calculated. A data-point was considered an outlier if its value was above $\tilde{x}+2\sigma$ or below $\tilde{x}-2\sigma$. The outliers were then excluded from the data, as seen in Figure 4-11.
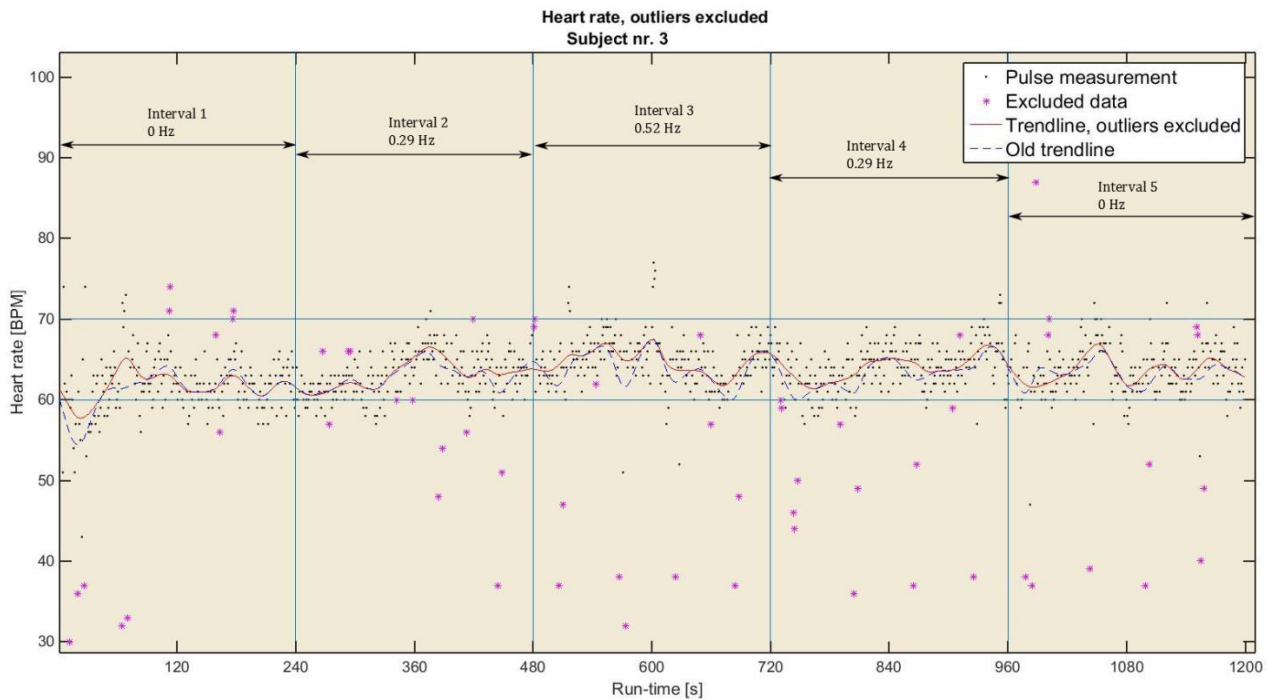
Figure 4-11 Heart rate data from one subject, outliers excluded. A new trend-line is fitted to the data, showing improvement from excluding outliers. Vertical line separate 4-minute intervals. Horizontal lines show 60 BPM and 70 BPM thresholds.

The heart rate data was divided into five intervals of 4 four minutes, corresponding to the five oscillation intervals of the experiment (See Table 4-1 and vertical lines in Figure 4-10 and Figure 4-11).

We do not want to include changes in heart rate due to disturbance caused when changing the frequencies. Each frequency change lasted approximately 20 seconds and we assume, based on experience from the pilot tests, that the effect of the change is insignificant at the end of the following 40 seconds. Data from the first 60 seconds of each interval was therefore excluded.

Our data showed that average resting heart rate varied from approximately 50 BPM for some subjects, to almost 100 BPM for others. This large inter-subject variability creates false

negative results in t-tests and analysis of variance (ANOVA). The data must therefore be normalized before it can be used in these tests[2].

We normalize the data using the procedures below. An excerpt of the List of Symbols and Abbreviations is shown in Table 4-2 for an explanation of the symbols used in the following.

Table 4-2 Explanation of symbols used in the data processing

Symbol	Explanation
i and j	Interval number
n	Subject number
x	Heart rate data point [BPM]
$\bar{x}_i^n$	Mean heart rate in interval i for subject n [BPM]
Δ_{ij}^n	Delta ij, difference in mean heart rate between interval i and j, for subject n.
$\bar{x}_{i,norm}^n$	Mean heart rate, normalized around 0
ϕ_i	Mean of normalised mean values of interval i

The mean heart rate of the remaining 3 minutes of each interval was calculated for each subject, producing $\bar{x}_i^n$-values.

The difference between all mean values were calculated for each subject, using the formula below:

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[2] We are studying the <u>change</u> in mean heart rate between intervals (Chapter 2 Aims, Chapter 5 Results). The actual pulse, in beats per minute (BPM), of each subject is not of interest in this study and we can therefore normalize our data without compromising our results.

$$\Delta_{ij}{}^n = \overline{x}_i{}^n - \overline{x}_j{}^n \qquad \qquad \textit{Equation 4-2}$$

These Delta-values were analysed using Students' t-tests. (See Appendix C2 for an explanation of Delta-values and results of t-tests.)

For use in ANOVA, $\overline{x}_i{}^n$-values were normalized around zero with the following procedure:

$$b^n = \frac{\overline{x}_1{}^n + \overline{x}_2{}^n + \overline{x}_3{}^n + \overline{x}_4{}^n + \overline{x}_5{}^n}{5}$$

$$\overline{x}_{i,norm}^n = \frac{\overline{x}_i{}^n}{b^n} - 1 \qquad \qquad \textit{Equation 4-3}$$

The Matlab ANOVA test calculates and compares the mean of all normalized values of each interval (ϕ_i):

$$\phi_i = \frac{1}{N} \sum_{n=1}^{N} \overline{x}_{i,norm}^n \qquad \qquad \textit{Equation 4-4}$$

5 Results

5.1 Acceleration

Acceleration was measured for all test subjects in intervals 2, 3 and 4 (see Chapter 4.1.3). The average rms-acceleration of each interval is shown in Table 5-1 below. The table also shows the theoretical rms-acceleration calculated in Chapter 3.5.5.

Table 5-1 Mean root-mean-square acceleration in x-direction

Mean root-mean-square acceleration	Interval 2	Interval 3	Interval 4
Measured, $\bar{a}_{x,rms}$ $\left[\dfrac{m}{s^2}\right]$	0.0882	0.2894	0.0843
Theoretical, $\left[\dfrac{m}{s^2}\right]$	0.1138	0.3995	0.1138

5.2 Heart rate

Six data-sets showed severe ECG-measurement errors in one or more intervals and were excluded from the analysis. One- and two-sided t-tests, analysis of variance (ANOVA) and Multiple comparison tests were performed on the remaining 34 data sets, using Mathworks Matlab 2014b. The Multiple comparison test, based on the results from ANOVA[3], proved to be more conservative than the t-tests and is therefore shown here. All test results are shown in Appendix C Test results. Subject data is shown in Appendix B Subject data. See Appendix C3 ANOVA and Multiple comparison for a discussion of assumptions used in ANOVA and Multiple comparison tests.

The Multiple comparison test compares the mean of normalized values, ϕ_i, against each other, producing a level of significance (p-value) for rejection of the null-hypothesis:

$$H0: \mu_i = \mu_j$$

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[3] See http://se.mathworks.com/help/stats/anova1.html and http://se.mathworks.com/help/stats/multcompare.html for further information about ANOVA and Multiple comparison tests in Matlab 2014b.

where μ_i and μ_j are the population mean of interval i and j, respectively.

Results of the Multiple comparison test for consecutive intervals are shown in Table 5-2 below.

Table 5-2 Results of Multiple comparison tests for consecutive intervals.
H0 is rejected for $\triangle_{34}$ at a 2% level of significance (green), indicating a significant difference in mean heart rate between interval 3 and 4. A positive estimated difference of means indicate that the mean of interval i ($ø_i$) is larger than the mean of interval j ($ø_j$).

					Multiple Comparison test		
Delta value	Interval i	-	Interval j	p-value	Lower confidence interval, 95%	Estimated difference of means $ø_i$ - $ø_j$	Upper confidence interval, 95%
Δ_{12}	1	-	2	**1,00**	-0,02	0,00	0,02
Δ_{23}	2	-	3	**0,66**	-0,01	0,01	0,03
Δ_{34}	3	-	4	**0,017**	0,00	0,02	0,04
Δ_{45}	4	-	5	**0,71**	-0,01	0,01	0,03

A box-plot provides an intuitive presentation of the differences between intervals and the spread in our data. Figure 5-1 show a box-plot of all $\overline{x}_{i,norm}$ -values utilized in the Multiple comparison in Table 5-2. In addition to the significant difference between interval 3 and 4 a general trend of decreasing heart rate can be observed. This is confirmed by the results of t-tests and Multiple comparison tests found in Appendix C Test results.
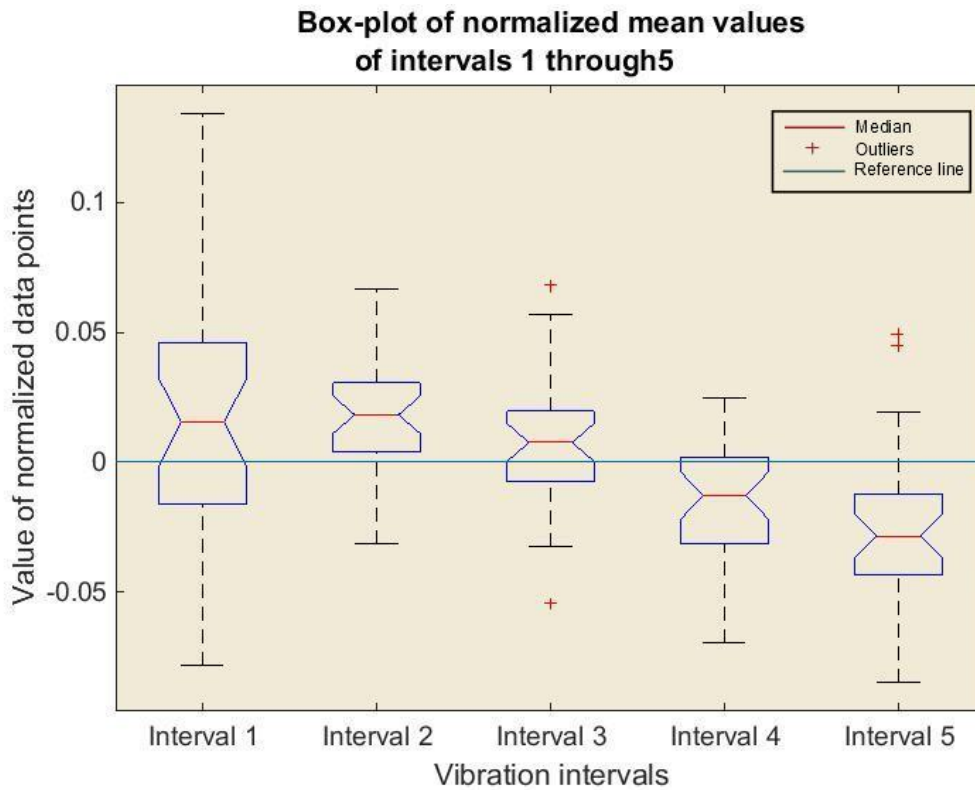
Figure 5-1 Box-plot of normalize mean values in all 5 intervals. Central red line is the median, box edges are the 25th (q1) and 75th (q3) percentiles. Whiskers extend to the most extreme points not considered outliers. Outliers are defined as values larger than $q_3 + 1.5*(q_3 - q_1)$ ***or smaller than*** $q_1 - 1.5*(q_3 - q_1)$ ***Notches represent comparison intervals. Two medians are different at the 5 % level of significance if their notches do not overlap.***

5.3 Groups within the sample

Different groups within our test subjects may show different results than the entire 36-subject sample. Multiple comparison tests were therefore performed on different groups of test subjects. The groups tested are listed in Table 5-3 below.

Table 5-3 Groups of test subjects, classified by listed criteria

Group number	Criteria
1	Female subjects
2	Male subject
3	Weight $\geq$ 80 kg

None of the groups showed a significant difference in mean between any consecutive intervals. However, all groups show the same declining trend as the entire sample. Results of each test are found in Appendix C4 Groups within the sample.

5.4 Duplicate tests

Four subjects were tested twice to investigate the consistency of the results. Of these, one subject showed extensive measurement errors and had to be excluded. The duplicate results of the remaining 3 subjects were compared and are shown in Figure 5-2.
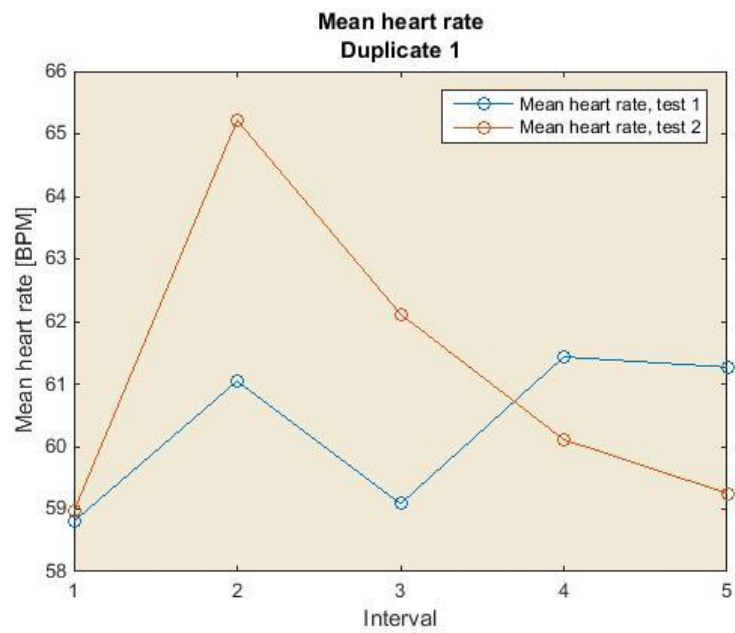
a)
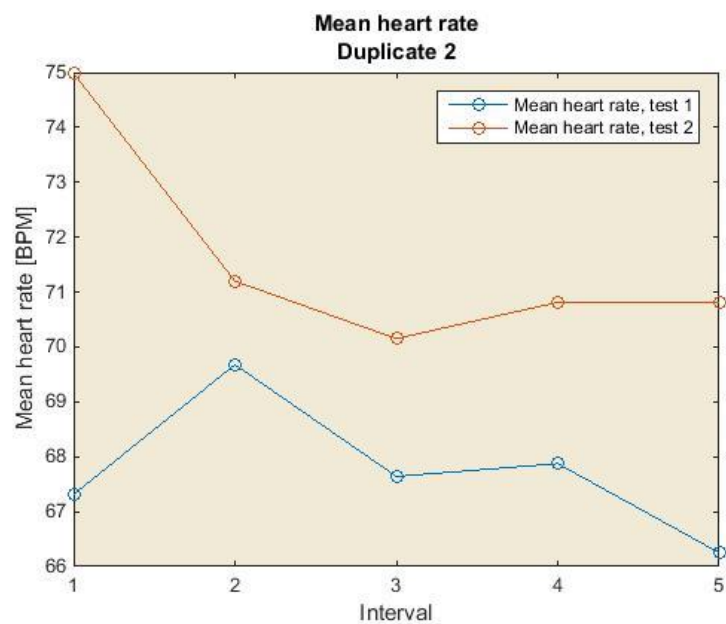
b)
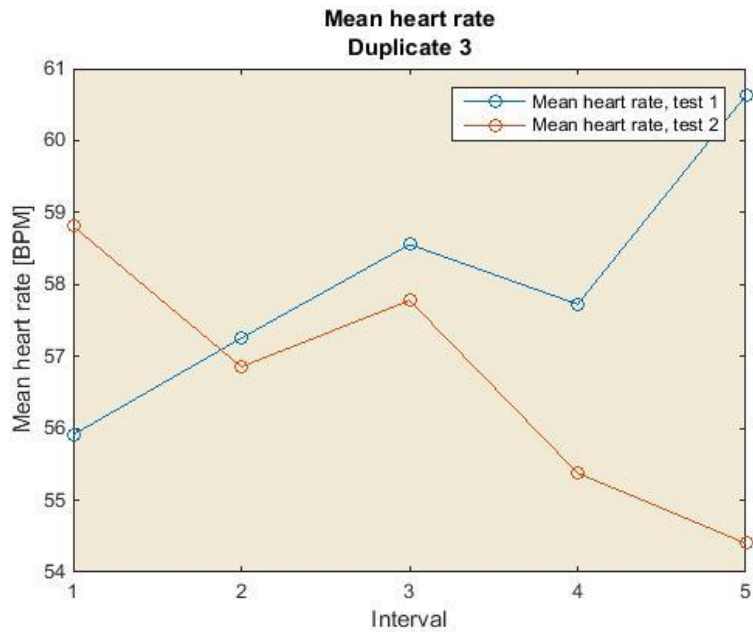
c)

**Figure 5-2 Comparison of duplicate results. l with connecting lines showing
the change-trend between intervals.**

As can be seen by Figure 5-2 **a** – **c**, the mean heart rate of each interval vary much within the
duplicate tests. In Figure **b** (duplicate 2) there appears to be a decrease – increase trend
between intervals 2, 3 and 4. In the same intervals, Duplicate 3 (Figure **c**) appears to have an
increase – decrease trend. In Figure **a** (Duplicate 1) it is difficult to see any clear trends.
Several more tests on each subject might have resulted in a clearer picture.

5.5 Rate of change

An analysis of the rate of change in heart-rate (slope) of all intervals was attempted but
abandoned due to time constraints. However, preliminary results suggested that the change
(positive, negative or neutral) in heart rate between intervals varied much between subjects.

30

6 Discussion

There is a significant decrease in heart rate between interval 3 and 4. This could indicate that lowering the vibration magnitude from a "bordering on annoying" high to a comfortable low helps the body to relax, or that the high magnitude in interval 3 agitated the subjects. However, there are no other significant changes between any other consecutive intervals. If lowering the magnitude helps the body to relax we would expect to see the same significant decrease between interval 4 and 5. It may be that the low vibration magnitude was too slight to have an effect on heart rate.

Furthermore, if the high magnitude agitated the subjects we would expected an increase in heart rate between interval 2 and 3. However, there's no significant change between either interval 1 and 2, or interval 2 and 3. (The t-test actually rejects H0 for Delta 23 ($p < 0.05$), but the ANOVA does not, see Appendix C2.) No change between interval 2 and 3 is surprising. We expected a clear response between these intervals due to the relatively large change in magnitude and forces on the body. (Pederson 1975) says that greater vibration magnitude (up to a point) is more effective in calming infants. We can speculate that the rise in magnitude kept the subjects heart rate from naturally sinking as they became more relaxed over time. However, when comparing individual test results it was seen that the effect of the vibrations varied much from person to person. Though most subjects had a slightly decreasing or relatively steady resting pulse, a number of subjects actually had a steadily rising pulse throughout the experiment. Quite surprising, considering that they were resting in a comfortable bed. A more thorough study of the rate-of-change (slope) between intervals could yield interesting results.

Although some subjects had a rising heart rate, a general trend of decreasing heart rate over time can be observed in Figure 5-1. (Supported by results found in Appendix C Test results.) This is not surprising as we would expect the heart rate to drop as the subjects become more relaxed. Several subjects even reported falling asleep during the experiment.

Interestingly, none of the subjects mentioned any form of motion sickness or nausea. Griffin (1990) indicates that frequencies around 0.2 Hz produce the most severe motion sickness in vertical vibrations. Perhaps the magnitudes in our experiments were too small to induce motion sickness, or perhaps the direction of motion has a deciding effect. This could be interesting to study further.

6.1 Error sources

6.1.1 Apparatus

The electric motor used in our test was not strong enough to produce a perfectly sinusoidal motion when exposed to the varying resistance from the mattress. The motion of the mattress therefore varied slightly, being somewhat slower than the average at the points of maximum resistance (the top points of the pendulum motion) and somewhat faster than average at the midpoint of the pendulum motion. This slight deviation from sinusoidal motion may have affected our results. It may also have been the cause of the difference in measured rms-acceleration from the theoretical value (Table 5-1).

Small deviations from the target frequencies of 0.286 Hz and 0.516 Hz were unavoidable. The commutator transformer was difficult to adjust precisely and the handheld tachometer is not a very accurate gauge. Deviations of $\pm 0.01 \, \text{Hz}$, as read by the tachometer, were therefore accepted when tuning the commutator transformer. Variation in the tachometer read-outs induced by unsteady hands adds to the deviations. However, it seems unlikely that these small errors should affect our results in any significant manner.

Many subjects described unexpected high-frequency vibrations in the mattress. The magnitude of these vibrations were too small to be detected by our accelerometer. Upon inspection we found the vibrations to originate from the connection joints at both sides of the connection arm, but we were not able to remove them altogether. Some subjects described them as "annoying". This may have had an impact on our results.

6.1.2 Subjective and environmental factors

Both environmental and subjective factors may have influenced our results. Chapter 0 and Griffin (1990) 41) describe a long list of factors that should be considered when conducting experimental studies on whole-body vibration. As our experiment was conducted in a workshop, most environmental factors were difficult or impossible to control. Room temperature, time of day and general level of activity in the workshop may have had an effect on our results. Even though subjects were given the option of using hearing protection and eye mask, background noise and differing light conditions can also have affected the results of our study, while sudden loud noises from the workshop can have resulted in jumps in heart rate.

The subjects of the study were all students and in a somewhat narrow age group (from 19 to 34 years of age). In addition, subjects' expectations of the experiment, social discomfort with resting with eyes closed in a busy area, subjects overall personality, age, sex and body position during the experiment can all have affected our results. The fact that the experiment was conducted during the exam period can also have affected the heart rate of many a poor subject.

6.1.3 Data gathering

The author has some concerns about the validity of data from interval 1. We expected to see a rapidly declining heart rate as the subjects lay down and rested, but there's no clear trend in the data. Although the test subjects were allowed to find comfortable positions and calm down before the measurements began, perhaps cutting off the first 60 seconds of measurements was not enough. The unfamiliar situation or other confounding factors could have contributed to the unexpected lack of change between interval 1 and 2 and interval 1 to 3.

In the process of identifying outliers we observed that many intervals had outliers in both the high and low range (Figure 4-11). This resulted in a very large standard deviation for the respective intervals and consequently broad inclusion criteria for data points. Some data-points were therefore not removed, although they clearly were outliers. A more advanced filtering algorithm or running the outlier definition code a second time, after the first outliers were removed, may have removed these points and resulted in less variance in the data.

6.2 Closing thoughts

It is difficult to conclude anything definite from our results. Overall, it appears to the author that the chosen vibration magnitudes have had very little effect on the subjects' heart rate. The slight decrease between interval 3 and 4, and the general sinking trend (Figure 5-1), can both be explained by the effect of the body relaxing over time. The large variations seen in the duplicate tests (Figure 5-2) also cast some doubts about the validity of our results. We expected to see clear and consistent changes in heart rate between each interval. The vibrations of highest magnitude were clearly felt, and some subjects even complained that the vibrations were on the edge of being annoying. The low magnitude vibrations, on the other hand, were described as comfortable and "relaxing once you got used to it".

It's hard to believe that the vibrations should have no physiological effect on the body whatsoever. It seems more reasonable to conclude that heart rate does not provide a good

measure of these effects. The heart rates' natural variation (Figure 4-11) seems to create too much noise to reliably detect possible changes due to the vibrations. In addition, it seems heart rate is too easily influenced by external factors and events to be a reliable variable in this type of study.

6.3 Further work

With more time, additional and more complex analyses could have been performed on our data and many correlations might have been uncovered. A thorough analysis of the rate of change (slope) in heart rate could yield interesting results and other statistical variables than mean could be used to describe the change in heart rate. Several tests on a single subject may also provide a clearer picture about the vibrations' effect.

Future studies, both on the Colicot cradle and otherwise, should consider additional physiological factors to monitor. Eri and Mevåg (2013) consider electroencephalography (EEG), capnography, electromyography (EMG), blood pressure and body temperature for monitoring the arousal level of infants in the Colicot cradle. All of these methods, and surely many others, may yield interesting results when studying the physiological effects of vibrations. Additional recommendations for the future development of the Colicot cradle are given in Appendix A Recommendations for Colicot AS.

There is an endless range of vibration frequencies and magnitudes one could study and future experiments must be tuned to fit their respective aims. Future studies must also consider whether the use of constant amplitude suits their aims. This will depend on whether the study seeks to examine the actual effect of the vibration, or, as is the case in this thesis, seeks to determine if there is an effect.

7 Literature

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APPENDICES

A Recommendations for Colicot AS

Regarding further studies on the effect of vibrations on humans, adults or infants, a good measurement of "activity level" must be found. With respect to infants, and considering the works of (Eri and Mevåg, 2014) while keeping REK's guidelines in mind, it is very possible that direct observation is the only feasible way to get any useful data.

During the user test of the Colicot cradle many areas of improvement were uncovered. Here follows a list of concerns or improvement suggestions the test-families had.

App'en må fikses på, den fungerer ikke optimalt og er litt for komplisert for noen personer

Bør re-designe vogga til å være hev / senk-bar

Om natta stå vogga ofte på soverommet. Da er det ikke så lurt med musikk.

For høye sidevegger, ungen føler seg isolert

Grønt lys fra kretskort er irriterende, må fjernes

Slitsomt å bøye seg ned til vogga om natta / gå ut av senga

Vogger i sengehøyde er vanligst nå. En vegg må da fjernes / felles ned for easy access

Vogge-høyden må justeres etter type seng

Fordel om samme vogge også kan brukes på gulvet

Appen er grei å bruke for en teknisk interessert, men kanskje litt unødvendig komplisert

Lyder er irriterende

Vogga tar opp litt mye gulvplass, bør ikke ta mye mer.

Vogga lager mye lyd når den vugger om natta

Stroppene strekker seg slik at vogga går i bakken, må ha sterkere stropper

B Subject data

Subject registration data

Subject number	Date	Time of day	Age	Weight	Height	Sex	Comment
1	04.12.2014	1045	23	87	175	m	
2	04.12.2014	1240	26	83	187	m	duplicate 36
3	04.12.2014	1320	24	70	180	m	
4	04.12.2014	1400	21	82	180	m	
5	04.12.2014	1430	21	60	175	f	
6	04.12.2014	1500	22	73	-	m	
7	04.12.2014	1630	23	80	180	m	duplicate 24
8	04.12.2014	1800	31	71	174	m	
9	04.12.2014	1845	26	75	180	m	
10	04.12.2014	1900	19	60	172	f	
11	04.12.2014	2000	20	79	182	m	duplicate 40
12	05.12.2014	1750	22	53	169	f	errors
13	05.12.2014	1600	24	70	178	m	Errors
14	05.12.2014	1700	25	100	185	m	errors
15	05.12.2014	1840	23	67	170	m	
16	05.12.2014	1900	22	70	182	m	duplicate 38
17	06.12.2014	1645	24	80	180	m	

18	06.12.2014	1715	34	52	160	f	
19	06.12.2014	1800	24	56	163	f	
20	07.12.2014	1310	23	80	192	m	errors
21	07.12.2014	1330	22	72	183	m	
22	07.12.2014	1400	24	81	182	m	
23	07.12.2014	1440	19	65	178	f	
24	07.12.2014	1600	23	80	180	m	duplikat 7
25	07.12.2014	1700	24	62	178	f	
26	07.12.2014	1730	27	70	175	f	
27	07.12.2014	1810	22	72	180	m	
28	07.12.2014	1915	24	80	183	m	errors
29	07.12.2014	1945	25	68	174	m	
30	07.12.2014	2015	25	70	183	m	
31	07.12.2014	2100	23	75	182	m	
32	08.12.2014	1110	30	80	182	m	
33	08.12.2014	1230	23	80	183	m	
34	08.12.2014	1300	23	78	190	m	
35	08.12.2014	1345	24	80	182	m	
36	08.12.2014	1445	26	83	187	m	duplikat 2, errors
37	08.12.2014	1530	24	80	186	m	
38	08.12.2014	1600	22	70	182	m	duplikat 16
39	08.12.2014	1820	23	102	180	m	
40	08.12.2014	1900	20	79	182	m	duplikat 11

C Test results

C1 Subject heart rate data

Subjects mean heart rate in interval 1 through 5.				
Subject number	$\bar{x}_1$ [BPM]	$\bar{x}_2$ [BPM]	$\bar{x}_3$ [BPM]	$\bar{x}_4$ [BPM]	$\bar{x}_5$ [BPM]
1	56	56	53	53	51
2	66	65	63	66	62
3	62	64	65	64	64
4	73	71	69	67	68
5	65	64	63	61	60
6	100	89	89	82	80
7	59	61	59	61	61
8	46	47	47	48	46
9	54	55	56	55	58
10	52	51	49	47	48
11	67	70	68	68	66
12	74	74	73	73	75
13	73	69	71	68	63
14	58	58	59	54	55
15	70	69	68	68	63
16	56	57	59	58	61
17	63	68	69	66	62
18	51	51	53	51	50
19	69	79	80	75	72
20	45	48	47	47	49
21	64	65	66	67	64

22	64	66	65	64	62
23	61	61	58	57	55
24	59	65	62	60	59
25	70	70	69	68	68
26	69	66	65	60	59
27	65	65	65	62	62
28	49	52	50	48	52
29	57	58	60	55	56
30	60	57	58	58	60
31	64	65	66	65	59
32	52	50	51	47	47
33	84	84	81	79	79
34	67	61	59	57	59
35	68	68	69	67	64
36	67	64	62	63	65
37	73	70	66	67	73
38	59	57	58	55	54
39	73	76	73	71	71
40	75	71	70	71	71

C2 T-tests

Both a one- and two-sided one-variable t-test was run on the Delta values. The table below explains the Delta-values used in the following chapters.

Explanation of the Delta-values used by the t-test. The 10 values below were calculated for each subject					
Delta	Δij	$=$	Interval **i**, $\bar{x}_i$	$-$	Interval **j**, $\bar{x}_j$
Delta 12	Δ_{12}	$=$	1	$-$	2
Delta 13	Δ_{13}	$=$	1	$-$	3
Delta 14	Δ_{14}	$=$	1	$-$	4
Delta 15	Δ_{15}	$=$	1	$-$	5
Delta 23	Δ_{23}	$=$	2	$-$	3
Delta 24	Δ_{24}	$=$	2	$-$	4
Delta 25	Δ_{25}	$=$	2	$-$	5
Delta 34	Δ_{34}	$=$	3	$-$	4
Delta 35	Δ_{35}	$=$	3	$-$	5
Delta 45	Δ_{45}	$=$	4	$-$	5

The two-sided t-test uses the formula $t = \dfrac{\overline{\Delta} - \mu}{s/\sqrt{n}}$ where μ is the hypothesized population mean, s

is the sample standard deviation and n is the sample size, to test the null-hypothesis $H0: \mu_i = 0$.

A H-value of 1 in the table below indicate that the test rejects H0 at the 5 % significance level, while H=0 signify that H0 stands.

Results of two-sided t-test on Delta values for all subjects. $H0: \mu = 0$								
TWO-SIDED T-TEST								
Delta	H	p-value	Lower confidence interval, 95%	Mean of delta values	Upper confidence interval, 95%	Value of test statistic	Degrees of freedom	Estimated population standard deviation.
12	0	**0,986**	-1,256	-0,011	1,233	-0,018	33	3,566
13	0	**0,364**	-0,800	0,662	2,124	0,921	33	4,190
14	1	**0,0091**	0,567	2,132	3,696	2,772	33	4,484
15	1	**0,0011**	1,197	2,765	4,332	3,589	33	4,492
23	1	**0,028**	0,079	0,673	1,267	2,305	33	1,702
24	1	**0,00001**	1,326	2,143	2,959	5,340	33	2,340
25	1	**0,00001**	1,701	2,776	3,851	5,252	33	3,082
34	1	**0,00036**	0,719	1,470	2,221	3,981	33	2,153
35	1	**0,00052**	0,991	2,103	3,215	3,846	33	3,188
45	0	**0,122**	-0,178	0,633	1,444	1,589	33	2,324

In the above table we see that for all intervals (except Delta 12) the "Mean of Delta values" is positive. We therefore run a one-sided t-test to confirm this and hope to gain better confidence levels. Again a H-value of 1 indicate that the test rejects H0 at the 5 % significance level, while H=0 signify that H0 stands.

The one-sided t-test tests the null-hypothesis: $H0: \mu_i > 0$

Results of one-sided t-test on all Delta values. $H0: \mu_i > 0$								
ONE-SIDED T-TEST								
Delta	H	p-value	Lower confidence interval, 95%	Estimated mean of Delta values	Upper confidence interval, 95%	Value of test statistic	Degrees of freedom	Estimated population standard deviation.
12	0	0,507	-1,0469	-0,011	Infinite	-0,018	33	3,566
13	0	0,182	-0,554	0,662	Infinite	0,921	33	4,190
14	1	0,0045	0,830	2,132	Infinite	2,772	33	4,484
15	1	0,0005	1,461	2,765	Infinite	3,589	33	4,492
23	1	0,014	0,179	0,673	Infinite	2,305	33	1,702
24	1	0,000003	1,464	2,143	Infinite	5,340	33	2,340
25	1	0,000004	1,881	2,776	Infinite	5,252	33	3,082
34	1	0,000178	0,845	1,470	Infinite	3,981	33	2,153
35	1	0,000260	1,178	2,103	Infinite	3,846	33	3,188
45	0	0,061	-0,041	0,633	Infinite	1,589	33	2,324

C3 ANOVA and Multiple comparison

The ANOVA makes the following assumptions about the input data:

1. All sample populations are normally distributed.

2. All sample populations have equal variance.

3. All observations are mutually independent.

The ANOVA test is known to be robust with respect to modest violations of the first two assumptions. (http://se.mathworks.com/help/stats/anova1.html)

In our experiment:

1. Is a reasonable assumption as each sample is large. Approximately 1200 data-point for each subject.

2. Studying the data-plots of each subject (like Figure 4-11) it's appears reasonable to assume that the natural variation in heart rate is relatively similar between subjects. In addition, ANOVA is robust with respect to violations of this assumption.

3. Each subjects' heart rate is independent from other subjects'. Each intra-subject heart rate data-point depends somewhat on previous data points. However, as can be observed in Figure 4-10and Figure 4-11, the heart rate can change very quickly. Jumps of 5 BPM and more can be observed from one data-point to the next. This makes the assumption of independence a reasonable one.

The Multiple comparison test uses the results of ANOVA and makes the same assumptions. See http://se.mathworks.com/help/stats/anova1.html and http://se.mathworks.com/help/stats/multcompare.html for further information about ANOVA and Multiple comparison tests in Matlab 2014b.

ANOVA returns a level of confidence (p-value) for the rejection of the null-hypothesis:

$$H0: \mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5$$

Results of ANOVA on all normalized mean heart rate values, $\bar{x}_{i,norm}^n$.					
ANOVA					
Source	Sum of squares due to each source (SS)	Degrees of freedom (df)	Mean square (MS=SS/df)	Ratio of mean squares (F)	**p-value**
Columns	0,051	4	0,01269	13,64	**1,24E-09**
Error	0,153	165	0,00093		
Total	0,204	169			

As can be seen in the table above H0 is rejected at a very high level of confidence, confirming that the normalized means ($\bar{x}_{i,norm}^n$) are not the same in all intervals.

Multiple comparison test results:

ANOVA does not say which intervals have different mean values. We therefore use a Multiple comparison test to compare each interval against the others. In each case testing the null-hypothesis:

$$H0: \mu_i = \mu_j$$

Results of Multiple comparison test for all subjects. $H0: \mu_i = \mu_j$						
Multiple Comparison test						
Intervall - i	Intervall j	p-value	Lower confidence interval, 95%	Estimated difference of means	Upper confidence interval, 95%	
1	- 2	**1,00**	-0,02	0,00	0,02	
1	- 3	**0,71**	-0,01	0,01	0,03	
1	- 4	**0,0001**	0,01	0,03	0,05	
1	- 5	**0,00000019**	0,02	0,04	0,06	
2	- 3	**0,66**	-0,01	0,01	0,03	
2	- 4	**0,00009**	0,01	0,03	0,05	
2	- 5	**0,00000012**	0,02	0,04	0,06	
3	- 4	**0,017**	0,00	0,02	0,04	
3	- 5	**0,00013**	0,01	0,03	0,05	
4	- 5	**0,71**	-0,01	0,01	0,03	

Interval	Mean	Standard error
1	1,0165	0,00523
2	1,0171	0,00523
3	1,0071	0,00523
4	0,9843	0,00523
5	0,9749	0,00523

C4 Groups within the sample

ANOVA and Multiple comparison tests were also run on different groups within the test-subjects. Table 5-3 shows the groups tested and is repeated below.

Groups of test subjects, classified by listed criteria

Group nr.	Criteria
1	Female subjects
2	Male subject
3	Weight $\geq$ 80 kg

Group 1 Female subjects

Results of ANOVA on female subjects

ANOVA

Source	Sum of squares due to each source (SS)	Degrees of freedom (df)	Mean square (MS=SS/df)	Ratio of mean squares (F)	**p-value**
'Columns'	0,0275	4	0,00688	7,267	**0,00032**
'Error'	0,0284	30	0,00095		
'Total'	0,0559	34			

Results of Multiple comparison tests on female subjects

Multiple comparison

Interval **i**	-	Interval **j**	**p-value**	Lower confidence interval, 95%	Estimated difference of means	Upper confidence interval, 95%
1	-	2	**0,990**	-0,055	-0,008	0,040
1	-	3	**0,992**	-0,040	0,007	0,055
1	-	4	**0,031**	0,003	0,051	0,099
1	-	5	**0,007**	0,013	0,061	0,109

			p-value	Lower confidence interval, 95%	Estimated difference of means	Upper confidence interval, 95%
2	-	3	**0,892**	-0,033	0,015	0,063
2	-	4	**0,010**	0,011	0,059	0,106
2	-	5	**0,002**	0,021	0,068	0,116
3	-	4	**0,084**	-0,004	0,044	0,092
3	-	5	**0,022**	0,006	0,054	0,101
4	-	5	**0,975**	-0,038	0,010	0,057

Group 2 Male subjects

Results of ANOVA on male subjects

ANOVA

Source	Sum of squares due to each source (SS)	Degrees of freedom (df)	Mean square (MS=SS/df)	Ratio of mean squares (F)	**p-value**
'Columns'	0,0286	4	0,00716	7,776	**0,000012**
'Error'	0,1197	130	0,00092		
'Total'	0,1483	134			

Results of Multiple comparison tests on male subjects

Multiple comparison

Interval **i**	-	Interval **j**	**p-value**	Lower confidence interval, 95%	Estimated difference of means	Upper confidence interval, 95%
1	-	2	**1,000**	-0,021	0,001	0,024
1	-	3	**0,746**	-0,013	0,010	0,033
1	-	4	**0,0082**	0,005	0,027	0,050
1	-	5	**0,00009**	0,014	0,037	0,059
2	-	3	**0,829**	-0,014	0,009	0,031
2	-	4	**0,014**	0,004	0,026	0,049
2	-	5	**0,00018**	0,013	0,035	0,058
3	-	4	**0,218**	-0,005	0,017	0,040
3	-	5	**0,011**	0,004	0,027	0,049
4	-	5	**0,793**	-0,013	0,009	0,032

Group 3 Subjects with weight > 80 kg

Results of ANOVA on subjects with weight > 80 kg

	ANOVA				
Source	Sum of squares due to each source (SS)	Degrees of freedom (df)	Mean square (MS=SS/df)	Ratio of mean squares (F)	**p-value**
'Columns'	0,0192	4	0,00481	6,415	**2,60E-04**
'Error'	0,0412	55	0,00075		
'Total'	0,0605	59			

Results of Multiple comparison tests on subjects with weight > 80 kg

Interval **i**	-	Interval **j**	**p-value**	Lower confidence interval, 95%	Estimated difference of means	Upper confidence interval, 95%
1	-	2	**0,76**	-0,0448	-0,0133	0,0183
1	-	3	**0,86176**	-0,0205	0,0110	0,0425
1	-	4	**0,165**	-0,0060	0,0256	0,0571
1	-	5	**0,013**	0,0057	0,0372	0,0688
2	-	3	**0,207**	-0,0073	0,0242	0,0558
2	-	4	**0,009**	0,0073	0,0388	0,0703
2	-	5	**0,0003**	0,0190	0,0505	0,0820
3	-	4	**0,69**	-0,0170	0,0146	0,0461
3	-	5	**0,15**	-0,0053	0,0262	0,0578
4	-	5	**0,83**	-0,0199	0,0117	0,0432

C5 Acceleration data

Subject nr.	Root-Mean-Square-Acceleration [m/s^2]				Interval 2	Interval 3	Interval 4
	Interval 2	Interval 3	Interval 4				
1	0,047	0,246	0,033		Mean	Mean	Mean
2	0,089	0,287	0,090		0,0882	0,2894	0,0843
3	0,088	0,261	0,078				
4	0,094	0,265	0,079		Std	Std	Std
5	0,096	0,274	0,096		0,0190	0,0203	0,0159
6	0,093	0,295	0,074				
7	0,096	0,303	0,099				
8	0,103	0,319	0,093				
9	0,120	0,328	0,108				
10	0,103	0,297	0,104				
11	0,091	0,282	0,079				
12	0,070	0,266	0,056				
13	0,111	0,317	0,103				
14	0,102	0,345	0,093				
15	0,083	0,315	0,086				
16	0,085	0,296	0,075				
17	0,086	0,276	0,073				
18	0,090	0,271	0,086				
19	0,109	0,299	0,101				
20	0,120	0,312	0,115				
21	0,115	0,302	0,110				
22	0,053	0,282	0,061				
23	0,100	0,303	0,092				
24	0,098	0,290	0,100				
25	0,096	0,305	0,089				
26	0,093	0,300	0,079				
27	0,088	0,280	0,082				
28	0,105	0,281	0,105				
29	0,073	0,272	0,075				
30	0,077	0,269	0,077				
31	0,084	0,258	0,087				
32	0,021	0,307	0,084				
33	0,083	0,287	0,075				
34	0,077	0,274	0,072				
35	0,095	0,299	0,086				
36	0,080	0,283	0,070				
37	0,083	0,291	0,078				
38	0,082	0,287	0,080				
39	0,077	0,276	0,080				
40	0,074	0,275	0,070				

C6 Pilot tests

A pilot test was run to establish what frequencies and amplitudes were best suited to our aims. The criteria considered were:

- Vibrations must be noticeable

- Vibrations must not be uncomfortable or disruptive for the subjects

- The frequencies interval should be as wide as possible to maximize the change in magnitude.

Amplitude of 5 cm and frequencies 0.29 Hz and 0.52 Hz were chosen for our study based on the above criteria.

Pilot test results

Amplitude [cm]	Frequency [Hz]	Theoretical peak acceleration [m/s^2]	Subjects' comment
12	0,21	0,209	Very calm, comfortable
12	0,25	0,292	Calm
12	0,29	0,389	Comfortable
12	0,40	0,762	Slightly uncomfortable
10	0,29	0,324	Comfortable
10	0,38	0,576	Slightly uncomfortable
10	0,48	0,900	Uncomfortable
10	0,52	1,050	Powerful jerk
7	0,29	0,227	Barely noticeable
7	0,38	0,403	Comfortable
7	0,57	0,907	Uncomfortable
5	0,02	0,001	Unnoticeable
5	0,29	0,161	Comfortable
5	0,52	0,525	Clearly felt, but not uncomfortable
5	0,57	0,648	Slightly annoying
5	0,76	1,152	Powerful jerk
3	0,29	0,097	Barely noticeable
3	0,38	0,173	Ok
3	0,57	0,389	Powerful jerk
3	0,76	0,691	Very powerful jerk

D Arduino code

```
#include <Wire.h>
#include <eHealth.h>
#include <SFE_MMA8452Q.h>
#include <SD.h>

float ECGsignal;
unsigned long timestamp;
String filNavn;
MMA8452Q aks;

// Sparkfun SD shield: pin 8
const int chipSelect = 8;

void setup()
{
  Serial.begin(9600);
  Serial.println("Test supercode with accelerometer and ECG!");
   pinMode(10, OUTPUT);
  if (!SD.begin(chipSelect)) {
    Serial.println("Card failed, or not present");
    return;
    }
  aks.init(SCALE_2G, ODR_6);
  ECGsignal=eHealth.getECG();
  Serial.println(ECGsignal);
 }

void loop()
{
  timestamp = millis();

  if (timestamp <= 600000) {
    filNavn = "ti.txt";
  }
   else if (timestamp > 600000, timestamp <= 1200000) {
    filNavn ="tjue.txt";
  }
    else if (timestamp > 1200000 && timestamp <= 1800000) {
    filNavn ="tretti.txt";
  }
  else  {
    filNavn ="overTretti.txt";
  }

  char navn[filNavn.length()+1];
     filNavn.toCharArray(navn, sizeof(navn));

     File csvFile = SD.open(navn, FILE_WRITE);

  if(csvFile){

     ECGsignal=eHealth.getECG();
     aks.read();

     csvFile.print(timestamp);
```

```
        csvFile.print(";");
        csvFile.print(ECGsignal);
        csvFile.print(";");
        csvFile.print(aks.cx, 3);
        csvFile.print(";");
        csvFile.print(aks.cy, 3);
        csvFile.print(";");
        csvFile.print(aks.cz, 3);
        csvFile.println(";");


        csvFile.close();
        }
  else{
      Serial.println("wtf, shit ain't working");

}

    }
```

E Matlab code

E1 Heart rate, individual subjects

```matlab
clear all;
fil1= load('ti.txt');
fil2 = load('tjue.txt');
%fil3 = load('tretti.txt');

dataFil = [fil1;fil2];
imax= length(dataFil);
y=dataFil(1:imax,2);
timestamp=dataFil(1:imax,1)/1000;

% Reversere data:
%{x
for i=1:length(dataFil)
    y(i,1)= 5 - dataFil(i,2);
end
%}

h = fir1(500,1/72*2,'high');
% filter out DC
y_filt=filter(h,1,y);
% square it
detsq = y_filt .^ 2;

% let's detect the momentary heart rate in beats per min
last=0;
upflag=0;
prePulse=zeros(length(detsq),1);
%avg_puls=zeros(length(detsq),1);
p=60;

% PULSE Calculations
for i = 1:length(detsq)
    if (detsq(i) > 1)
        if (upflag == 0)
            if (last > 0)
                t = timestamp(i) - last;
                p = uint8(60/t);
            end
            last =timestamp(i);

        end
        upflag = 35;
    else
        if (upflag>0)
            upflag = upflag - 1;
        end
    end
    prePulse(i)=p;
end

pulse=zeros(length(prePulse),2);
pulse(1,2)=prePulse(1);
```

```matlab
pulse(1,1)=timestamp(1);
for i=2:length(prePulse)
    if (prePulse(i)~= prePulse(i-1))
        pulse(i,1) = timestamp(i);
        pulse(i,2) = prePulse(i);
    end
end

pulse( ~any(pulse,2), : ) = [];
heartRate=pulse(:,2);
time=pulse(:,1);


fit1 = fit(time, heartRate, 'smoothingspline', 'SmoothingParam', 0.0005);


I=[]; %zeros(length(heartRate),1);
a=zeros(30,1);

for j=30:30:(length(heartRate))
    v=heartRate(j-29:j);
    medi=median(v);
%  a ~= v > 1.3*medi
%     for k=1:20
        a= abs(v-medi) > 2*std(v);
%         if (abs(v(k)-mean(v)) > 1.5*std(v))
%             I(end+1)=v(k);
%         end
%     end
    I=[I;a];
end
I=logical(I);



outliers = excludedata(time,heartRate,'indices',I);
fit2 = fit(time, heartRate, 'smoothingspline', 'SmoothingParam', 0.0005,
'Exclude', outliers);

% SAVE STUFF
%{
save('pulse.mat', 'pulse');
save('indices.mat', 'I');
%}
%{x
figure('Color',[0.8 0.8 0.8]);
plot(fit2, 'r-', time, heartRate, 'k.', outliers, 'm*')
 hold on
plot(fit1,'b--')
p_legend=legend('Pulse measurement', 'Excluded data', 'Trendline, outliers
excluded', 'Old trendline');
set(p_legend,'FontSize', 18);
line([240, 240],[30,110])
line([480, 480],[30,110])
line([720, 720],[30,110])
line([960, 960],[30,110])
refline(0,60)
refline(0,70)
%refline(0,80)
```

```matlab
title('Heart rate, outliers excluded Subject nr. 3','FontSize',16)
xlabel('Run-time [s]','FontSize',16)
ylabel('Heart rate [BPM]','FontSize',16)
set(gca,'Color',[0.941 0.917 0.839],'linewidth',1.5);


%}
%savefig('pulsePlot.fig')
% PLOT Y
%{
figure('Color',[0.8 0.8 0.8]);
plot(timestamp,y)
set(gca,'Color',[0.941 0.917 0.839])
legend('ECG-signal')
xlabel('Time')
ylabel('Signal strength [v]')
xlim([450,460])
title('ECG signal  Subject nr. 3')
%}

% PLOT Y_FILT
%{
figure
plot(y_filt)
title('Y-Filt')
%}

% PLOT detsq
%{
figure('Color',[0.8 0.8 0.8]);
h=subplot(1,1,1);
plot(timestamp,detsq)
set(h,'Color',[0.941 0.917 0.839])
legend('Filtered signal')
xlabel('Run-time [s]')
ylabel('Signal')
xlim([450,460])
title('Filtered signal  Subject nr. 3')

%}

% PLOT PULSE
%{
figure('Color',[0.8 0.8 0.8]);
plot(timestamp,prePulse)
set(gca,'Color',[0.941 0.917 0.839])
refline(0,60)
refline(0,70)
refline(0,80)
title('Heart-rate Subject nr 3','FontSize',14)
xlabel('Run-time [s]','FontSize',14)
ylabel('Heart rate [BPM]','FontSize',14)
legend('Momentary heart rate')
%}
%{x
figure('Color',[0.8 0.8 0.8]);
plot(fit1, 'b-', time, heartRate, 'k.')
```

```matlab
h_legend=legend('Pulse measurement', 'Trendline');
set(h_legend,'FontSize', 18);
line([240, 240],[30,110])
line([480, 480],[30,110])
line([720, 720],[30,110])
line([960, 960],[30,110])
refline(0,60)
refline(0,70)
%refline(0,80)
title('Heart rate Subject nr. 3','FontSize',16)
xlabel('Run-time [s]','FontSize',16)
ylabel('Heart rate [BPM]','FontSize',16)
set(gca,'Color',[0.941 0.917 0.839]);
%}
```

E2 Heart rate data analysis

```matlab
clear all
%load('c:\Users\PLM\Dropbox\Arduino\MATLAB\testdata\mean_and_slope.mat');
%load('c:\Users\PLM\Dropbox\Arduino\MATLAB\testdata\Ttests.mat');
load('mean_and_slope.mat');
load('Ttests.mat');
% data: 1, 4, 7, 10 og 13 = middelverdi
% data: 2, 5, 8, 11 og 14 = std for middelverdien
% data: 3, 6, 9, 12 og 15 = slope

% Remove samples with clear errors
%{x
removeSample=zeros(length(data),1);
removeSample([12 13 14 20 28 36])=1;
removeSample=logical(removeSample);
data(removeSample, :)=[];
Ttestdata(removeSample, :)=[];
%}
my1=data(:,1);my2=data(:,4);my3=data(:,7);my4=data(:,10);my5=data(:,13);
allmys=[my1,my2,my3,my4,my5];

delta12=my1-my2;delta13=my1-my3; delta14=my1-my4; delta15=my1-my5;
delta23=my2-my3; delta24=my2-my4; delta25=my2-my5;
delta34=my3-my4; delta35=my3-my5;
delta45=my4-my5;

deltas=[delta12, delta13, delta14, delta15, delta23, delta24,...
    delta25, delta34, delta35, delta45];

% Calculate number of tests with positive, neutral, or negative slope
%(1st interval)
%{x
slope0=data(:,3)*100;
positiveSlope=0;
negativeSlope=0;
neutralS=0;
for i=1:length(data)
    if (slope0(i) < -1)
        positiveSlope=positiveSlope+1;

    elseif (slope0(i) > 1)
        negativeSlope=negativeSlope + 1;
    else
        neutralS = neutralS+1;
    end
end
%}
% Produce scatterplot and histograms
%{x
    %{x
v=zeros(length(data),1);
for k=1:length(data)
    v(k)=k;
end
```

```matlab
pl=zeros(3,3);
figure('Color',[0.8 0.8 0.8]);
for i=1:9
    navn=strcat('Delta ',num2str(i));
    pl(i)=subplot(3,3,i);
    plot(deltas(:,i),v,'*')
    xlim([-12,12])
    title(navn)
end
set(pl,'Color',[0.941 0.917 0.839])
    %}
hist=zeros(2,5);
figure('Color',[0.8 0.8 0.8]);
for i=1:10
    navn=strcat('Delta ',num2str(i));
    hist(i)=subplot(2,5,i);
    histfit(deltas(:,i),20)
    xlim([-18,18])
  % plotter linje for middelverdien til Delta
    [muhat,sigmahat] = normfit(deltas(:,i));
    hold on;
    plot([muhat muhat],[0 8],'g','linewidth',1.5);
    title(navn)
end
set(hist,'Color',[0.941 0.917 0.839])
%}

% t-tests, right sided
results=zeros(10,8);
for i=1:10
    [h,p,ci,stats]=ttest(deltas(:,i),0,'Tail','right');
    results(i,1)=h;
    results(i,2)=p;
    results(i,3)=ci(1);
    results(i,4)=mean(deltas(:,i));
    results(i,5)=ci(2);
    results(i,6)=stats.tstat;
    results(i,7)=stats.df;
    results(i,8)=stats.sd;
end
B={'Delta 12','Delta 13','Delta 14','Delta 15','Delta 23','Delta 24',...
    'Delta 25','Delta 34','Delta 35','Delta 45'};
boxplot(deltas,B,'notch','on')
%refrefline(0,0)
```

E3 ANOVA and Multiple comparison testing

```
clear all
%load('c:\Users\PLM\Dropbox\Arduino\MATLAB\testdata\mean_and_slope.mat');
%load('c:\Users\PLM\Dropbox\Arduino\MATLAB\testdata\Ttests.mat');
load('mean_and_slope.mat');
load('Ttests.mat');
% data: 1, 4, 7, 10 og 13 = middelverdi
% data: 2, 5, 8, 11 og 14 = std for middelverdien
% data: 3, 6, 9, 12 og 15 = slope

% Remove samples with clear errors
%{x
removeSample=zeros(length(data),1);
removeSample([12 13 14 20 28 36])=1;
removeSample=logical(removeSample);
data(removeSample, :)=[];
Ttestdata(removeSample, :)=[];
%}
my1=data(:,1);my2=data(:,4);my3=data(:,7);my4=data(:,10);my5=data(:,13);
allmys=[my1,my2,my3,my4,my5];


delta1=my1-my2;delta2=my2-my3;delta3=my3-my4;delta4=my4-my5;
% gjennomsnitt av intervall 1 og 5 mot intervall 3
delta153=(my1+my5)/2 -my3;
% gjennomsnitt av intervall 2 og 4 mot intervall 3
delta243=(my2+my4)/2-my3;
delta15=my1-my5;
delta24=my2-my4;
delta35=my3-my5;
deltas=[delta1, delta2, delta3, delta4,delta15, delta24, delta35];
testDelta=[delta1, delta2, delta3, delta4];
B={'Interval 1','Interval 2','Interval 3','Interval 4', 'Interval 5'};

% All
%{x
nymy=zeros(length(allmys),5);
for i=1:length(allmys)
    middel=mean(allmys(i,:));
    nymy(i,:)=allmys(i,:)./middel-1;
end
[p,t,stats] = anova1(nymy,B);
figure
[c,m,h,nms] = multcompare(stats);
%}

% Female
%{x
j=allmys([5 10 15 16 19 21 22],:);
jenter=zeros(length(j),5);
for i=1:length(j)
    middel=mean(j(i,:));
    jenter(i,:)=j(i,:)./middel-1;
end

[p,t,stats] = anova1(jenter,B);
```

```matlab
figure
[c,m,h,nms] = multcompare(stats);
%}
% Male
%{x
gutter=allmys([1:4 6:9 11:14 17 18 20 23:34],:);
for i=1:length(gutter)
    middel=mean(gutter(i,:));
    gutter(i,:)=gutter(i,:)./middel-1;
end

[p,t,stats] = anova1(gutter,B);
figure
[c,m,h,nms] = multcompare(stats);
%}
% Weight > 80
%{x
tung=allmys([1 2 4 7 14 18 20 27 28 30 31 33],:);
for i=1:length(tung)
    middel=mean(tung(i,:));
    tung(i,:)=tung(i,:)./middel-1;
end
[p,t,stats] = anova1(tung,B);
figure
[c,m,h,nms] = multcompare(stats);
%}
%duplicates
%{x
%7 og 20, 11 og 34,  13 og 32
figure('Color',[0.8 0.8 0.8]);
subplot(3,1,1)
plot(allmys(7,:),'-o')
hold on
plot(allmys(20,:),'-o')
title({'Mean heart rate, Duplicate 1'})
legend('Mean heart rate, test 1','Mean heart rate, test 2')
xlabel('Interval')
ylabel('Mean heart rate [BPM]')
set(gca,'Color',[0.941 0.917 0.839],'linewidth',1,'XTick',[1,2,3,4,5]);

%figure('Color',[0.8 0.8 0.8]);
subplot(3,1,2)
plot(allmys(11,:),'-o')
hold on
plot(allmys(34,:),'-o')
title({'Mean heart rate, Duplicate 2'})
legend('Mean heart rate, test 1','Mean heart rate, test 2')
xlabel('Interval')
ylabel('Mean heart rate [BPM]')
set(gca,'Color',[0.941 0.917 0.839],'linewidth',1,'XTick',[1,2,3,4,5]);

%figure('Color',[0.8 0.8 0.8]);
subplot(3,1,3)
plot(allmys(13,:),'-o')
hold on
plot(allmys(32,:),'-o')
```

```
title({'Mean heart rate, Duplicate 3'})
legend('Mean heart rate, test 1','Mean heart rate, test 2')
xlabel('Interval')
ylabel('Mean heart rate [BPM]')
set(gca,'Color',[0.941 0.917 0.839],'linewidth',1,'XTick',[1,2,3,4,5]);
%}
```

E4 Acceleration processing

```matlab
clear all;
fil1= load('ti.txt');
fil2 = load('tjue.txt');
%fil3 = load('tretti.txt');

dataFil = [fil1;fil2];
datax=dataFil(16000:64000,3);
ax=datax-mean(datax);

ax1=ax(10000:15000);
ax2=ax(25000:30000);
ax3=ax(40000:45000);

X1=[];
X2=[];
X3=[];
for j=500:500:length(ax1)
        a1=ax1(j-499:j);
        X1=[X1,a1];
        a2=ax2(j-499:j);
        X2=[X2,a2];
        a3=ax3(j-499:j);
        X3=[X3,a3];
end
rmsverdi1=zeros(1,10);
rmsverdi2=zeros(1,10);
rmsverdi3=zeros(1,10);
for i=1:10
    r1=rms(X1(:,i));
    rmsverdi1(1,i)=r1;
    r2=rms(X2(:,i));
    rmsverdi2(1,i)=r2;
    r3=rms(X3(:,i));
    rmsverdi3(1,i)=r3;
end

rms1=mean(rmsverdi1(1,:));
rms2=mean(rmsverdi2(1,:));
rms3=mean(rmsverdi3(1,:));
rmsdata=[rms1,rms2,rms3];
%figure
%plot(ax)

% data=[];
% load('c:\Users\PLM\Dropbox\Arduino\MATLAB\testdata\acceleration_data.mat');
% data=[data;rmsdata];
%
save('c:\Users\PLM\Dropbox\Arduino\MATLAB\testdata\acceleration_data.mat','dat
a');
```

F Technical data

El-motor

Name: BEVI

Model: 2AL 712

Type: SKn 71X-4C2

Class: F

RPM: 1400

Power: 0.55 kW

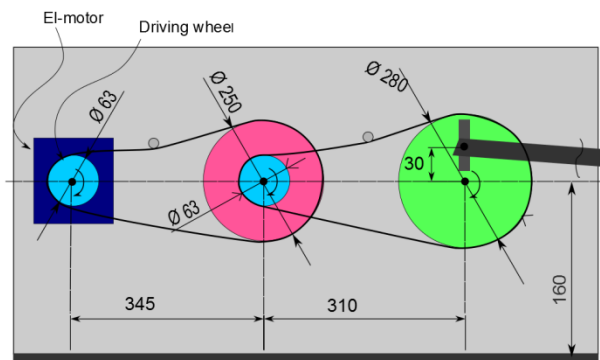Ampere: 3.65 A

Voltage: 230 V

Commutator transformer

Name: Scandailogic VPM

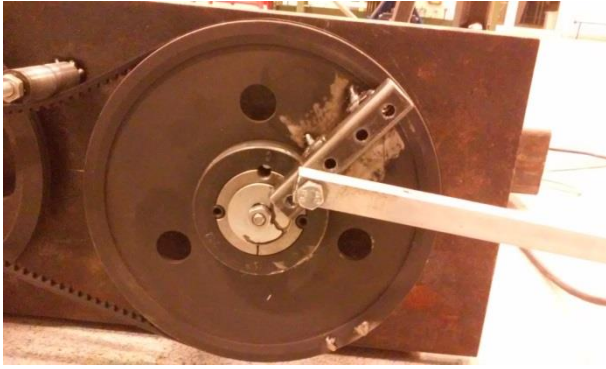Model: SL

Gearing

Pulley wheels: 2x 63 mm, 1x 250 mm 1x 280 mm.

Belts: 2x XPZ 1230 mm

Connector arm

Length: 1520 mm

Crane and wires

Length of wires: 4.5 m

Type of wire: Biltema presenningsnor Ø8 polypropylene

Mattress

Dimensions: 2000 mm x 1200 mm x 220 mm (lxbxh)

Standard framed mattress.

Eye mask

Asaklitt sleeping mask 31-8230

Hearing protection

Peltor Optimei

Measurement system / data gathering

Arduino module: Arduino UNO R3

E-Health module: Cooking hacks' e-Health sensor platform V2.0 with electrocardiogram sensor

Accelerometer: SparkFun Tripple Axis Accelerometer breakout - MMA8452Q

Kendall ECG electrodes

G Problem text

MASTER THESIS AUTUMN 2014
FOR
STUD.TECHN. DAG FREDRIK NEDBERG

HARMONIC VIBRATIONS' INFLUENCE ON HUMAN PHYSIOLOGY
Harmoniske bevegelsers innvirkning på menneskelig fysiologi

Vibrations that affect humans are experienced practically everywhere in our environment, from the low frequency, harmonic vibrations found in baby-cradles to high frequency, non-stationary random vibrations found near heavy traffic. "Human vibrations", or "human response to whole-body vibration", is wide and multi-disciplinary field that still requires a lot of research to be fully understood.

To gain a better understanding of human response to low frequency, harmonic vibrations, such as an infants' response to a cradles rocking motion, we want to study the physiological reactions in humans subjected to this kind of vibration.

The project will consist of the following:

- Review literature on human response to vibrations, measurement procedures and test setups
- Build a suitable test setup
- Monitor physiological response in adult humans to low frequency, harmonic vibrations.
- Monitor change in physiological factors in response to changing frequencies.
- Prepare a draft to publish a paper with our findings

Three weeks after start of the thesis work, an A3 sheet illustrating the work is to be handed in. A template for this presentation is available on the IPM's web site under the menu "Masteroppgave" (http://www.ntnu.no/ipm/masteroppgave). This sheet should be updated one week before the Master's thesis is submitted.

Performing a risk assessment of the planned work is obligatory. Known main activities must be risk assessed before they start, and the form must be handed in within 3 weeks of receiving the problem text. The form must be signed by your supervisor. All projects are to be assessed, even theoretical and virtual. Risk assessment is a running activity, and must be carried out before starting any activity that might lead to injury to humans or damage to materials/equipment or the external environment. Copies of signed risk assessments should also be included as an appendix of the finished project report.

The thesis should include the signed problem text, and be written as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents, etc. During preparation of the text, the candidate should make efforts to create a well arranged and well written report. To ease the evaluation of the thesis, it is important to cross-reference text, tables and figures. For evaluation of the work a thorough discussion of results is appreciated.

The thesis shall be submitted electronically via DAIM, NTNU's system for Digital Archiving and Submission of Master's thesis.

Torgeir Welo
Head of Division

Martin Steinert
Professor/Supervisor

H Risk assessment

Kartlegging av risikofylt aktivitet

	Utarbeidet av	Nummer	Dato
	HMS-avd.	HMSRV2601	22.03.2011
	Godkjent av	Side	Erstatter
	Rektor	1 av 1	01.12.2006

Enhet: IPM

Deltakere ved kartleggingen (m/ funksjon): Martin Steinert (supervisor), Dag Fredrik Nedberg (student)

Dato: 29.09.14

Kort beskrivelse av hovedaktivitet/hovedprosess:

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
1	Activities in workshop			Workshop safety course		
2	Office work					
3	Research on human subjects					
4	Use of test equipement					
5	Use of crane					

Risikovurdering

	utarbeidet av	Nummer	Dato
	HMS-avd.	HMSRV2603	04.02.2011
	godkjent av	side	Erstatter
	Rektor	1 av 3	9.2.2010

Enhet: IPM

Linjeleder:

Deltakere ved risikovurderingen (m/ funksjon): Martin Steinert(supervisor), Dag Fredrik Nedberg (student)

Dato: 01.10.14

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet (1-5)	Vurdering av konsekvens: Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)	Risiko-verdi	Kommentarer/status Forslag til tiltak
1a	Welding	Personal injury. Eye damage.	2	d			b	D2	Difficult / hazardous welding work will be done or supervised by workshop personnel.
1b	Heavy lifting	Personal injury. Back injury.	2	d			b	D2	Heavy objects should be lifted by trucks operated by workshop personnel.
1c	Heavy objects falling from height	Personal injury. Head trauma.	2	d		c		D2	Heavy objects above chest level must be properly secured / fastened.
1d	Use of workshop tools	Personal injury	4	b				B4	Workshop procedures and safety requirements must be followed.
2a	Loss of power	Loss of data	3				b	B3	Frequent saving of work to server.
2b	Using computer	Elbow /arm inflammation	2	b				B2	Regular breaks. Ergonomic equipment.
2c	Prolonged sitting	Back pain	3	b				B3	Regular breaks. Ergonomic equipment.
3a	Ethical issues	Complaint from test subject	3				b	B3	Informed consent forms must be signed by all participants

NTNU	HMS/KS	Risikovurdering	utarbeidet av	Nummer	Dato
			HMS-avd.	HMSRV2603	04.02.2011
			godkjent av	side	Erstatter
			Rektor	2 av 3	9.2.2010

3b	Complaint from ethical committee		3		b	B3	Ensure all regulations are followed.
4a	Test equipment failure	Personal injury, test subject	3		b	B3	Equipment must be thoroughly tested and secured
4b		Personal injury, staff	2		b	B2	Equipment must be thoroughly tested and secured
4c		Equipment damage	3		b	B3	Equipment must be thoroughly tested and secured
5a	Lifting people with crane	Fall from height, personal injury	3		b	b	b	b	B3	Use safety harness. Supervised by workshop personel. Max height 2 m.

Sannsynlighet
1. Svært liten
2. Liten
3. Middels
4. Stor
5. Svært stor

Konsekvens
A. Svært liten
B. Liten
C. Moderat
D. Alvorlig
E. Svært alvorlig

Risikoverdi (beregnes hver for seg):
Menneske = Sannsynlighet x Konsekvens Menneske
Ytre miljø = Sannsynlighet x Konsekvens Ytre miljø
Økonomi/materiell = Sannsynlighet x Konsekvens Øk/materiell
Omdømme = Sannsynlighet x Konsekvens Omdømme

Sannsynlighet vurderes etter følgende kriterier:

Svært liten 1	Liten 2	Middels 3	Stor 4	Svært stor 5
1 gang pr 50 år eller sjeldnere	1 gang pr 10 år eller sjeldnere	1 gang pr år eller sjeldnere	1 gang pr måned eller sjeldnere	Skjer ukentlig

Konsekvens vurderes etter følgende kriterier:

Gradering	Menneske	Ytre miljø Vann, jord og luft	Øk/materiell	Omdømme
E Svært Alvorlig	Død	Svært langvarig og ikke reversibel skade	Drifts- eller aktivitetsstans >1 år.	Troverdighet og respekt betydelig og varig svekket
D Alvorlig	Alvorlig personskade. Mulig uførhet.	Langvarig skade. Lang restitusjonstid	Driftsstans > ½ år Aktivitetsstans i opp til 1 år	Troverdighet og respekt betydelig svekket

NTNU		Risikomatrise	utarbeidet av	Nummer	Dato
			HMS-avd.	HMSRV2604	08.03.2010
HMS/KS			godkjent av	side	Erstatter
			Rektor	2 av 2	09.02.2010

KONSEKVENS

		Svært liten	Liten	Middels	Stor	Svært stor
KONSEKVENS	Svært alvorlig		1a, 1b, 1c			
	Alvorlig		1a, 1b, 1c			
	Moderat				1d	
	Liten	2b, 4b	2a, 2c, 3a, 3b, 4a, 4c	1d		
	Svært liten					

SANNSYNLIGHET